Shorebird Habitat Use and Macroinvertebrate Composition in Robbins Passage/Boullanger Bay wetlands, NW Tasmania

by

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Declaration

This thesis contains no material which has been accepted for a degree or diploma by the University of any other institution, except by the way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text.

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Abstract

Virtually all species of shorebirds are decreasing on a global scale, due primarily to habitat loss and/or modification, through wetland reclamation, increased coastal erosion, decreased water quality and rising sea levels due to climate change. Many shorebirds are migratory and travel thousands of kilometres between their breeding grounds in Siberia and Alaska, to their winter feeding grounds in Australia, with over 2 million shorebirds arriving each year. These winter feeding grounds are crucial for the shorebirds' survival, supplying an abundant and predictable source of food for the birds, and places where they can roost undisturbed. The Robbins Passage/Boullanger Bay wetlands in northwest Tasmania are the most important shorebird site in Tasmania, supporting over 25,000 shorebirds each summer. As a primary site and the end point of the migratory shorebird network, and for its intrinsic values, it is important to investigate the ecology of the wetland and the habitat requirements of the shorebirds, before the area is modified or affected by increasing agriculture and coastal development within its catchments. The overall aim of this study therefore was to investigate how shorebirds use the resources of coastal wetlands at a local regional scale within the Robbins Passage/Boullanger Bay wetlands, to allow for the effective and sustainable management and conservation of the shorebirds and the wetlands as a whole. The present study investigated the habitats used by feeding and roosting shorebirds within the wetlands, and the relationships among physical environmental and biological variables, in addition to developing the first roost choice model for shorebirds in temperate Australia.

In order to investigate shorebird feeding habitat use, the spatial variation of intertidal macroinvertebrates were determined. In general, the mid-intertidal stratum had the greatest invertebrate density and diversity, while the low intertidal stratum had the greatest biomass. Seagrass biomass, i.e. dry mass of seagrass leaves and roots, partly explained the differences in invertebrate composition and abundance among and within sites, with sites with seagrass having increased invertebrate abundance and diversity.

The investigation of the low tide foraging distribution of shorebirds over the tidal flats within the Robbins Passage/Boullanger Bay wetlands showed that shorebird distribution within and among sites was non-random. The greatest densities and numbers of shorebirds were found at Shipwreck Point and East Inlet, the sites with the greatest invertebrate densities, and the greatest invertebrate biomass and species diversity, respectively. Palaearctic shorebirds were only found at Shipwreck Point and East Inlet. Within each site, the greatest shorebird densities were observed along the waters edge and low intertidal stratum, where invertebrate biomass was greatest, although shorebird distribution varied among species. Generally, on a small spatial scale, invertebrate diversity was positively correlated, and seagrass leaf mass negatively correlated, with shorebird feeding density, while on a larger spatial scale, invertebrate biomass and seagrass root mass were positively correlated with shorebird feeding density. Seagrass may inhibit the feeding method of some shorebird species, such as pied oystercatchers, as they tended to feed in areas where seagrass biomass was low. The larger spatial scale produced a stronger relationship between shorebird distribution and environmental variables.

Shorebird habitat use during the ebbing tide concurred with low tide habitat use, with the greatest densities and numbers of shorebirds occurring at both Shipwreck Point and East Inlet. Shorebird abundance was only significantly different at East Inlet and Robbins Passage, with shorebirds observed in greatest numbers two hours before low tide at East Inlet and four and zero hours before low tide at Robbins Passage. During the ebbing tidal cycle, the feeding distribution of pied oystercatchers was generally greater along the water's edge and the low intertidal stratum, while red-necked stints were observed along the water's edge and low intertidal stratum in greater numbers at East Inlet, and mid-intertidal stratum at Shipwreck Point.

Shorebirds used traditional roost sites throughout the wetlands, and while all roosts were used consistently over the 18-month period, total shorebird abundance and species richness fluctuated significantly over the seasons. The greatest numbers of roosting shorebirds occurred during the summer months, December to February, when the Palaearctic species (e.g. Pacific golden

plover, red-necked stint and ruddy turnstone) were present in greater numbers, due to their arrival from their breeding grounds in the northern hemisphere. Resident shorebird species were generally observed roosting in greater numbers during autumn and winter when they had completed their breeding season, as compared to summer and spring.

The number and species of shorebirds at each roost site also varied, with six times the mean number of birds found at East Shipwreck Point as compared to the other sites. Shorebird roost choice appeared to be driven by the distance of the roost from the feeding grounds and the width of the site. These factors allow the birds to reduce their energy expenditure by roosting near feeding areas and decreasing the flying distance, and minimise the risk of predation, as a wider site provides greater distance to cover for potential predators. The roost choice model had an overall classification success rate of 87.5%.

Further work is required in the Robbins Passage/Boullanger Bay wetlands, but these results can be used to assist in the development of management plans for the wetlands and the conservation of important shorebird areas, as well as contributing to the growing body of information on shorebird habitat use and providing a roost choice model for temperate coastal Australia.

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Preface

This PhD thesis is composed of five free-standing papers, and as such, there is a degree of repetition in the description of the study area and methodologies. To streamline the structure of the thesis, I have removed the addresses, keywords and acknowledgements from each paper; but I have maintained the reference list and appendices for each. I am the first author on all of these papers and my co-authors are my two supervisors.

The five data chapters for publication are as follows:

Chapter 2: Spatial variation of intertidal macroinvertebrates and environmental variables in Robbins Passage wetlands, NW Tasmania. *Hydrobiologia.* 2007. 598, 325-342.

Chapter 3: Influence of environmental and prey variables on low tide shorebird habitat use within the Robbins Passage wetlands, Northwest Tasmania. *Estuarine, Coastal and Shelf Science.* 2008. 78, 122-134.

Chapter 4: Influence of tidal level on coastal habitat use by shorebirds within the Robbins Passage/Boullanger Bay wetlands, Northwest Tasmania.

Chapter 5: Spatial and temporal variation of roost use in the Robbins Passage/Boullanger Bay wetlands and south-east Victoria.

Chapter 6: High-tide shorebird roost choice in temperate coastal Australia. submitted.

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Chapter 1
Introduction

The single greatest threat facing shorebirds is habitat loss and/or modification, through land reclamation, disturbance and climate change (Warnock *et al.*, 2002; Birdlife International, 2004b). These changes are already resulting in decreases in shorebird populations worldwide (IWSG, 2003), with a number of studies finding that the decreases in shorebird numbers are linked specifically to disturbance or loss of shorebird roost or feeding sites (e.g. Mitchell *et al.*, 1988; Goss-Custard & Yates, 1992; Pfister *et al.*, 1992; Burton *et al.*, 1996). Wetlands and estuaries, which are the main habitats of shorebirds, due to the diversity of areas that they provide for feeding, roosting and breeding (Vermeer & Butler, 1994), are also threatened globally and are still decreasing alarmingly (Finlayson & Rea, 1999). In Australia alone, it is believed that more than 50% of wetlands have been lost to various land use changes since European settlement (Finlayson & Rea, 1999). Only recently has the true importance of wetlands been recognised, and much effort is now being made towards their restoration and conservation in Australia and around the world (Costanza *et al.*, 1997; Finlayson & Mitchell, 1999; Finlayson & Rea, 1999; Young *et al.*, 2001). Given this context of globally decreasing shorebird habitats, it is essential to understand the birds' specific habitat requirements in these coastal areas, in order to conserve or replace these habitats.

Shorebirds

Shorebirds, or waders, belong to the order Charadriiformes (Sub-order Charadrii) and there are 75 shorebird species in Australia, making up approximately 10% of Australia's avifauna. Twenty-nine species are found in Tasmania (Table 1). The majority (76%) of Australian shorebird species are migratory, with the remaining 18 species year-round residents (Lane, 1987). Shorebirds are found in a number of different habitats in Australia, including salt lakes and inland wetlands, agricultural land and beaches, but their greatest numbers are seen in coastal wetlands.

Table 1. Resident shorebirds and regular migrant shorebirds in Tasmania, listed in taxonomic order.

Scientific name	Common name	Tas. status	EPBC listed	IUCN listed
Gallinago hardwickii	Latham's Snipe		•	
Limosa lapponica	Bar-tailed Godwit		•	
Numenius phaeopus	Whimbrel		•	
Numenius madagascariensis	Eastern Curlew	e	•	
Tringa nebularia	Common Greenshank		•	
Xenus cinereus	Terek Sandpiper		•	
Actitis hypoleucos	Common Sandpiper		•	
Heteroscelus brevipes	Grey-tailed Tattler		•	
Arenaria interpres	Ruddy Turnstone		•	
Calidris tenuirostris	Great Knot		•	
Calidris canutus	Red Knot		•	
Calidris alba	Sanderling		•	
Calidris ruficollis	Red-necked Stint		•	
Calidris melanotos	Pectoral Sandpiper		•	
Calidris acuminata	Sharp-tailed Sandpiper		•	
Calidris ferruginea	Curlew Sandpiper		•	
Haematopus longirostris	Pied Oystercatcher*			
Haematopus fuliginosus	Sooty Oystercatcher*			
Pluvialis fulva	Pacific Golden Plover		•	
Pluvialis squatarola	Grey Plover		•	
Charadrius ruficapillus	Red-capped Plover*		•	
Charadrius bicinctus	Double-banded Plover		•	
Charadrius mongolus	Lesser Sand Plover		•	
Elseyornis melanops	Black-fronted Dotterel*			
Thinornis rubricollis	Hooded Plover*		•	NT
Vanellus tricolor	Banded Lapwing*			
Vanellus miles	Masked Lapwing*			
Sterna albifrons	Little Tern*	e	•	
Sterna nereis	Fairy Tern*	r	•	

*resident shorebirds
Endangered (e): Those species in danger of extinction because long term survival is unlikely while the factors causing them to be endangered continue operating.
Rare (r): Those species with a small population in Tasmania that are at risk
NT: near threatened on IUCN list of threatened species.
• listed as a migratory or marine species under the EPBC Act 1999.

Of the migratory shorebirds that visit Australia, most breed in the Northern Hemisphere, predominantly in Alaska, Siberia and northern China. Their breeding habitats range from Arctic tundra to shingle beaches, areas which are snow free for only a short time each year. This puts the birds on very tight migration and breeding schedules, arriving at their breeding grounds in early June, and leaving mid- to late July, after their chicks have fledged. During this short summer, the shorebirds take advantage of a rich food source, the insect population that explodes during the brief Arctic summer (Lane, 1987; Priest *et al.*, 2002).

Travelling to their winter feeding grounds from their summer breeding areas, the shorebirds follow a low number of known migratory routes called flyways, eight of which are recognised around the world. The East Asian-Australasian Flyway (EAAF) is the route used by birds travelling from the Northern Hemisphere to east Asia, Australia and New Zealand; it may involve crossing stretches of ocean of up to 6000km. The birds complete the journey in a number of stages, utilising stopover sites for feeding along the flyway. These wetland sites provide food for the birds to regain body reserves in the form of fat for the next stage of their journey. The EAAF extends through 22 countries and over 12,000km between the shorebirds' nesting sites and their final destination (Lane, 1987; Priest *et al.*, 2002; Warnock *et al.*, 2002). It is estimated that approximately 5 million shorebirds head south along the EAAF each northern summer. However, the EAAF is under enormous human pressure in the Asian region, which contains over a third of the world's human population and where more than 80% of the significant wetlands are classified as threatened in some way (Barter, 2002; IWSG, 2003). It is estimated that 58% of the world's globally threatened wader species (32 species) are found in the Asia and Oceania regions, 12 of which use the EAAF, and none of which are increasing in numbers, while over 50% of the known number of Scolopacidae (sandpipers) and Charadriidae (plovers) populations are decreasing (IWSG, 2003; Wetlands International, 2006).

Of the estimated 5 million shorebirds that use the EAAF annually, a proportion overwinters on feeding grounds in eastern Asia, but over 2 million reach Australia, with Tasmania at the southern-most end. The shorebirds start arriving in northern Australia in high numbers in late August and early September, with many arriving in southern Australia shortly after (Lane, 1987). The shorebirds may then start their northward migration to their breeding grounds as early as mid-February, however the majority depart from Australia in March and early April. Juvenile shorebirds (i.e. 6-8 months old) may spend the whole year in Australia, not returning to their breeding grounds until their second or third year (i.e. at 18-30 months of age) (Lane, 1987). The shorebirds spend the southern summer feeding, moulting and depositing fat reserves for the return flight to their northern breeding grounds. The requirements of these non-breeding habitats are an abundant and predictable supply of food, allowing the birds to prepare for the breeding season, and areas for the birds to rest close to feeding areas. These summer habitats are critical to the birds' survival. The protection and conservation of migratory shorebirds and their habitats is therefore a joint, multilateral effort among many countries, as their breeding, wintering and stopover sites extend from one end of the Earth to the other.

Research

The ecology and distribution of coastal shorebirds has been a focus of research for many years in the Northern Hemisphere (Bengtson & Svensson, 1968; e.g. Goss-Custard *et al.*, 1977b; Zwarts & Wanink, 1993; Burton & Armitage, 2005; Goss-Custard *et al.*, 2006). The distribution of coastal shorebirds has been extensively studied (e.g. Goss-Custard *et al.*, 1977b; Symonds *et al.*, 1984; Kalejta & Hockey, 1994), as have their feeding ecologies (Goss-Custard *et al.*, 1977a; Goss-Custard, 1985), and prey distributions (Bryant, 1979; Kalejta & Hockey, 1994). In Australia however, shorebird research has only started to gather momentum in the last decade or two, as the importance of wetland habitats and their biota became clear. Moreton Bay in southeast Queensland has been the subject of numerous studies into feeding habitat use by eastern curlews and bar-tailed godwits (Congdon & Catterall, 1994; Zharikov & Skilleter, 2002; Finn *et al.*, 2007), while Dann (1999a; Dann, 1999b) has investigated feeding ecology of red-necked stints and curlew sandpipers in south-east Victoria. In northern New South Wales, Rohweder & Baverstock (1996) and Rohweder (2001) studied migratory shorebird habitat use at night.

Studies investigating shorebird habitat use in conjunction with invertebrate distributions on the tidal flats and other physical environmental variables have been undertaken in the Coorong in South Australia (Paton *et al.*, 2001) and in Roebuck Bay in northwest Western Australia, the site of probably the most intensive shorebird studies in the country (Tulp & de Goeij, 1994; Piersma *et al.*, 2002; Rogers *et al.*, 2006a). While these studies investigate feeding and roosting habitat use by shorebirds on a regional scale, they also endeavour to increase our knowledge of shorebird ecology on local and global scales.

Study Site

Tasmania is at the southern-most end of the EAAF, and thus is the end point of the migratory route for the shorebirds. If there is no available habitat in Tasmania, the shorebirds have nowhere else they can go, making it important on a national, and international, scale. Within Tasmania, the most important area for shorebirds is the Robbins Passage/Boullanger Bay wetlands in far northwest Tasmania, which is listed as a nationally important wetland (Young *et al.*, 2001; Woehler, 2007). The area supports internationally significant numbers of five migratory species of shorebird: curlew sandpipers, double-banded plovers, red knot, red-necked stints, and ruddy turnstones, and is of national importance for two resident species: pied and sooty oystercatchers (see Table 1 for scientific names of all species mentioned here). The wetlands qualify for listing under the Ramsar Convention, meeting the criteria that the area regularly supports 1% of the individuals of a population of shorebird (Woehler, 2007; WWF Australia, 2007).

Due to the relatively remote location, little research has been conducted in the Robbins Passage/Boullanger Bay wetlands, with the major roosts only being identified relatively recently (Ashby, 1991), and no previous studies have investigated any aspect of shorebird ecology within the wetlands. Surveys in 1996/97 collected baseline information on sediments, macrobenthic invertebrates and fish from 48 Tasmanian estuaries (Edgar *et al.*, 1999a). Two of the estuaries sampled, Welcome Inlet and Mosquito Inlet, are close to the Robbins Passage/Boullanger Bay wetlands, but they represent only a very small fraction of the vast intertidal flats (approximately 65km^2) present in the area. Apart from this study and the biannual bird surveys by the community-based group Birds Tasmania since 1993, no other work has been conducted on this area, Tasmania's most important coastal wetland.

The most serious threat facing the world's birds is habitat destruction, and the single most important cause of habitat destruction is expansion of agriculture (Birdlife International, 2004b). In Australia, agriculture and coastal development are the primary factors in habitat destruction, causing problems for shorebirds and biodiversity as a whole (Kennish, 2002; Priest *et al.*, 2002). Northwest Tasmania is also subject to these issues. The Robbins Passage/Boullanger Bay wetlands are in a relatively undisturbed condition with little modification, but as coastal development increases, so will the variety and intensity of the pressures on the wetland increase. The majority of the human population in the region live within 1km of the coast, and this is also where population growth is the greatest, as coastal land is becoming increasingly valued for residential and tourism development (CC-NRM Committee, 2005). Areas adjacent to the wetlands and within the catchment area are already compromised to varying extents from clearing of native vegetation for agriculture, forestry, and urban and industrial developments, leading to increased sediment runoff into the wetlands and reduced water quality. There has also been a recent switch in land use in the catchment from extensive cattle grazing to intensive dairying, which has further affected water quality through increased fertiliser use. Approximately 30% of Tasmania's salt marsh, one of the most threatened vegetation communities in the State, is found within the Robbins Passage/Boullanger Bay wetlands, where it is threatened by exotic weeds such as rice grass (*Spartina anglica*), cattle grazing and recreational off-road vehicles, as are the shorebirds and their habitats (CC-NRM Committee, 2005). As a primary site of the international migratory shorebird network, and for its intrinsic values, it is important to investigate the ecology of the wetland and the habitat requirements of shorebirds in temperate coastal Australia, before the area is modified or affected by these changes and developments.

The overall aim of this study therefore was to investigate how shorebirds use the resources of coastal wetlands at a local regional scale within the Robbins Passage/Boullanger Bay wetlands, to allow for the effective and sustainable management and conservation of the shorebirds and the wetlands as a whole. While other studies have been undertaken on a local regional scale, few studies, and none in temperate Australia, have endeavoured to investigate feeding and roosting habitat use in a local wetland for the shorebird population as a whole. The majority of studies have been species-specific (e.g. Dann, 1991; Congdon & Catterall, 1994; Dann, 1999b; Finn *et al.*, 2007), and most have had a basis of previous studies to build on. Studies in Roebuck Bay, northwest Western Australia investigated feeding and roost habitats in tropical Australia, but were primarily interested in red and great knots (e.g. Tulp & de Goeij, 1994; Rogers, 1999; Rogers *et al.*, 2006a), reflecting the body of Northern Hemisphere studies on red knots. This study aimed to gather a holistic view of shorebird use within the wetlands. The study investigated the habitats used by feeding and roosting shorebirds within the wetlands, and the relationships among physical environmental and biological variables, in addition to developing a roost choice model for shorebirds in temperate Australia, which has never been attempted before. As the wetlands are indeed vast (over 100km^2) it was not feasible to have sites throughout the entire area, due to issues of accessibility, logistics and safety considerations. Four sites within the wetlands were therefore selected in an attempt to encompass a range of sediment types and vegetation cover, and take in different areas of the wetlands. Four sites were also seen as a reasonable number to study over an 18-month period.

To achieve the aims of this study, chapter two investigates and compares macroinvertebrate composition, abundance and biomass at four sites within the wetlands. This information is utilised in chapter three, which investigates the roles of a number of variables in determining the choice of foraging habitat by shorebirds within the wetlands, namely prey abundance and distribution, and habitat characteristics. Chapter four describes the patterns of foraging by shorebirds over the tidal cycle. Chapters five and six explore the way in which shorebirds use roosts: chapter five examines roost use at a number of roosts within the Robbins Passage/Boullanger Bay wetlands and compares these with two other wetland complexes in southeast Australia. Chapter six focuses on the environmental variables that influence roost choice by shorebirds and develops a roost choice model for shorebirds in temperate coastal Australia. This is followed by a general discussion and conclusions in chapter seven. References and Appendices are listed at the end of each chapter.

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Chapter 2

Spatial variation of intertidal macroinvertebrates and environmental variables in Robbins Passage wetlands, NW Tasmania.

Abstract

Macroinvertebrate composition, abundance and biomass were investigated at four intertidal sites throughout the Robbins Passage/Boullanger Bay wetlands, Tasmania, over a 12-month period, in order to identify differences among and within sites, and to determine whether environmental variables could explain these differences. As this region is the most important shorebird area in Tasmania, we wanted to quantify the potential food source for shorebirds within the wetlands. Thirty-five taxa from 28,928 individuals were identified, with a mean abundance of 6026.6ind.m^{-2} and biomass of 27.1gDW.m^{-2}. Bivalves and gastropods dominated the assemblage in terms of abundance and biomass (79% and 60%, respectively). There was a significant interaction among tidal level, site and season for invertebrate abundance and diversity, while biomass differed significantly among sites. In general, the mid-intertidal stratum had the greatest invertebrate density and diversity, while the low intertidal stratum had the greatest biomass. Community composition varied among the four sites, with the bivalve *Paphies elongata* dominating at two of the sites, while gastropods and polychaetes were more abundant at the other sites. Differences in invertebrate composition and abundance could partly be explained by seagrass biomass, i.e. dry mass of seagrass leaves and roots. Areas with seagrass had increased invertebrate abundance and diversity, but mean sediment particle size, % organic carbon and % seagrass cover had no significant effect. These results will assist in the investigation of habitat use by shorebirds and the identification of important shorebird feeding areas within the wetlands.

Introduction

Intertidal flats, areas of the coast that are alternately covered and uncovered by tidal action, are dynamic ecosystems, providing food and habitat for many organisms. Intertidal benthic invertebrate communities are a vital part of these ecosystems and an important food source for terrestrial predators such as shorebirds as well as marine predators such as fish. These invertebrate communities change on spatial and temporal scales (Ysebaert & Herman, 2002; Rodrigues *et al.*, 2006). Knowledge of their composition and distribution is essential to understand an intertidal ecosystem and its processes, and more specifically, feeding, habitat use and distribution of shorebirds.

Many studies have investigated the distribution (Chainho *et al.*, 2006; Rodrigues *et al.*, 2006), abundance (Kalejta & Hockey, 1991; Dittman, 2002b), diversity (Boehs *et al.*, 2004) and biomass (Masero *et al.*, 1999; Silva *et al.*, 2006) of invertebrates on intertidal flats. There have also been many studies that examine the effect of environmental variables on invertebrate abundance and community composition (Anderson, 1972; Castel *et al.*, 1989; Edgar & Barrett, 2002). Sediment type and size are important in determining the composition of the invertebrates that live in the intertidal flats (Defeo & McLachlan, 2005), and influencing invertebrate abundance and biomass (Dankers *et al.*, 1981; Ysebaert & Herman, 2002). The presence of seagrass is also thought to increase invertebrate diversity and abundance (Edgar *et al.*, 1994; Heck *et al.*, 1995; Lee *et al.*, 2001), with seagrass biomass, not structural complexity, being the important factor (Attrill *et al.*, 2000).

On a local scale, zonation of soft-sediment tidal flats is a result of tidal level and consequently exposure time, and sediment composition (Peterson, 1991; Edgar, 2001). Predation by fish (at high tide) and birds (at low tide) can also result in some zonation along the flats (Peterson, 1991; Defeo & McLachlan, 2005). The influence of tidal height on macroinvertebrate diversity, abundance and biomass has been found to vary, depending on the study and location (Dankers *et al.*, 1981; Dittman, 2002b; Edgar & Barrett, 2002).

Invertebrate studies on tidal flats have been undertaken all around the world (Kalejta & Hockey, 1991; Heck *et al.*, 1995; Dittman, 2002b; Rodrigues *et al.*, 2006). However, of the limited amount of work that has been done in Tasmania (Moverley & Jordan, 1996; Edgar & Barrett, 2002), most has been concentrated around the populated southeast, with only a few baseline or monitoring studies conducted in the more remote northwest of the island (but see Edgar *et al.*, 1999b). However, the wetlands in this region support over 25,000 shorebirds during the summer months, the highest concentration in Tasmania, and the area is of international significance to migratory shorebirds (Dunn, 2001; Woehler & Park, 2006). It is therefore imperative that we understand why the Robbins Passage/Boullanger Bay wetlands are so attractive to shorebirds, and that these values are maintained. The potential food source for the birds may be the primary factor influencing their fine-scale distributions within the wetlands. The main aim of this study therefore was to investigate and compare the macroinvertebrate richness of four sites within the Robbins Passage/Boullanger Bay wetlands, as shorebird food sources. This was further refined as the investigation of macroinvertebrate diversity, abundance and biomass, at various intertidal habitats, within the Robbins Passage/Boullanger Bay wetlands, and to evaluate the relationships among the invertebrates and several environmental factors. The results of this study will be incorporated with shorebird feeding data (Spruzen *et al.*, 2008) to develop a predictive model of shorebird habitat use. Two specific questions were addressed:

1. What are the patterns of variation in the macroinvertebrate composition, abundance and biomass among the sites and over the tidal flat at each site?
2. Can the measured environmental variables be used to predict variation in macroinvertebrate composition, abundance and biomass within and among sites?

Materials and methods

Study area

The Robbins Passage/Boullanger Bay wetlands make up a coastal intertidal system located in the far northwest of Tasmania (40° 40'S, 144° 50'E) with an area of over 100km^2 (Fig. 1) (Dunn, 2000). They consist of two large shallow tidal basins, Boullanger Bay and Big Bay. The wetlands are an extensive area of tidal channels and intertidal sand flats, comprising approximately 65% of the total site area, with a mean tidal range of 3.5m (DPIWE, 1999b; Dunn, 2000). The wetland contains one of the most important areas of seagrass beds in Tasmania, dominated by *Posidonia australis* (Hook.f.), and cover an area of approximately 8000 ha (Rees, 1993; DPIWE, 1999b). The extensive intertidal areas provide habitat for resident and migratory shorebirds, with over 25,000 shorebirds recorded in summer months, more than all other sites in Tasmania combined (Woehler & Park, 2006). The wetlands are a site of international significance for five migratory shorebird species: curlew sandpipers (*Calidris ferruginea* (Pontoppidan, 1763)), double-banded plovers (*Charadrius bicinctus* (Jardine & Selby, 1827)), red-necked stints (*Calidris ruficollis* (Pallas, 1776)), red knot (*C. canutus* (Linnaeus, 1758)) and ruddy turnstones (*Arenaria interpres* (Linnaeus, 1758)), and of national importance for two resident species: pied (*Haematopus longirostris* (Vieillot, 1817)) and sooty oystercatchers (*Haematopus fuliginosus* (Gould, 1845)) (Watts, 1999; Woehler, 2007). Recent land use changes in the wetlands catchments are potential factors threatening the shorebirds in the area.

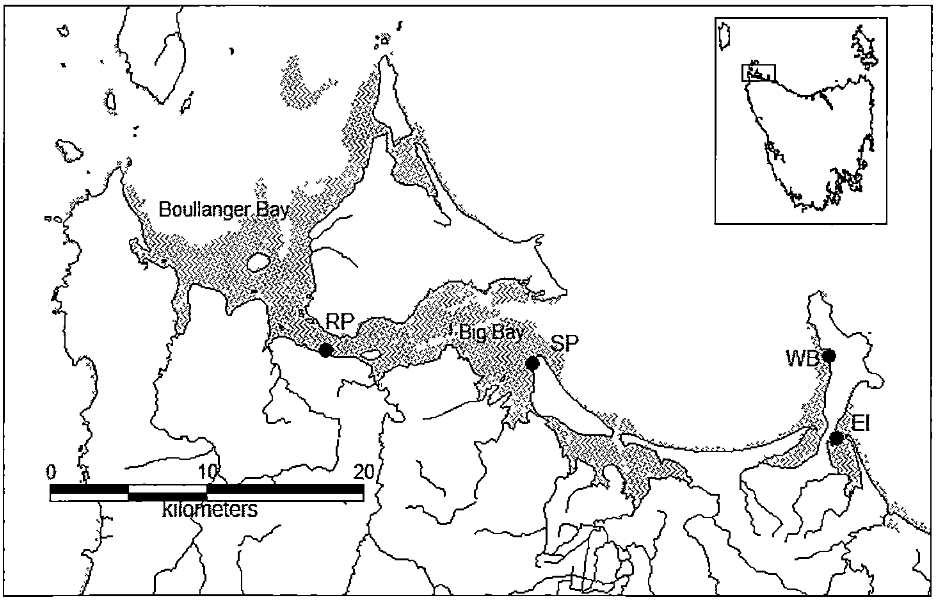

Figure 1. Map of northwest Tasmania, showing the location of the invertebrate sampling sites. Hatched areas represent tidal flats. (EI = East Inlet, RP = Robbins Passage, SP = Shipwreck Point, WB = West Beach)

Sampling design

The macroinvertebrate fauna was investigated at four intertidal flats, East Inlet (EI), Robbins Passage (RP), Shipwreck Point (SP) and West Beach (WB), in the Robbins Passage/Boullanger Bay wetlands spanning a linear range of 33kms (Fig. 1). The sites were chosen to encompass a range of sediment types and vegetation cover, although the choice of sites was also influenced by accessibility, logistics and safety considerations. The invertebrate sampling was carried out at the four sites every three months beginning January 2005 and ending January 2006, resulting in five sampling events. At each site a 400m transect, parallel to the shoreline and extending from the high water to the low water mark, was established. Each site was equally divided into three strata: low, mid- and high intertidal sections and 10 random cores (diameter = 100mm ($0.008m^{-2}$), depth = 150mm) were collected from each stratum at each site. A total of 30 cores were collected at each site (10 cores x 3 strata) within an hour of daylight low tide.

The cores were sieved on site using a 1.0mm Endecott sieve, and all material retained on the sieve was fixed in 5% formalin. Rose bengal stain was added to the fixative to assist in the sorting of biological material. In the laboratory, the samples were once again washed through a 1.0mm mesh sieve before being sorted, identified and counted. Polychaetes, crustaceans and molluscs were identified to species level whenever possible, although names could not always be provided. Very small gastropods were grouped together as it was difficult to distinguish between species while sorting. Holothurians and anthozoans were classified to family level, and nemerteans and sipunculids to phylum level (Honkoop *et al.*, 2006). As some taxa were only identified to broad taxonomic levels, the species list is not comparable with other studies, however a comprehensive species list was not the aim of this study.

The cores from each stratum were then pooled and the dry weight biomass of each taxonomic group was recorded (Southwood & Henderson, 2000; Silva *et al.*, 2006). As some of the invertebrate samples were too small to provide adequate material for biomass analysis, they were regrouped into broader taxonomic groups, although taxonomic resolution was limited to a level of discrimination likely to be used by the birds (Dann, 1987). The groups used for biomass analysis were: amphipods, isopods, crabs, shrimps (Penaeidae and Callianassidae), other crustaceans, gastropods, mytilidae, *Paphies* species (*Paphies elongata* and *Paphies* sp.), other bivalves, polychaetes, worms and others. The samples were separated into size classes, dried at 90°C for 40 hours and then weighed. A sub-sample of molluscs was used to calculate length-weight regressions to estimate shell-free dry mass from shell length (Hartley *et al.*, 1987; Southwood & Henderson, 2000).

Environmental variables

A sediment sample was collected from each intertidal stratum at each site with a 50mm diameter corer pushed to a depth of 50mm. Only a single sediment sample was collected at each site during the 12 month period, as we were not primarily interested in change over time. Once collected the samples were frozen for later analyses. In the laboratory, the sediment was dried at 70°C for 48 hours and sieved through a nested series of Endecott sieves (0.063, 0.125, 0.25, 0.5, 1, 2mm mesh sizes) to determine sediment particle size distribution. Sieve fractions were expressed as a percent of the total sediment sample and mean sediment particle size (phi, from the Udden-Wentworth scale) calculated (Anderson, 2006). Sediment particles less than 1.0mm were then recombined and a small sub-sample taken to measure total organic content. This sample was re-dried at 70°C for 24 hours, weighed and then treated with 1M hydrochloric acid to remove shell material (carbonates) (Hirst *et al.*, 2005). The sample was then redried, reweighed and incinerated in a muffle furnace at 500°C for 4hrs, before being weighed again, and the organic content of the sediment expressed as a percentage of the total weight (Kingsford & Battershill, 1998; Paton *et al.*, 2001).

Seagrass collected in the invertebrate cores was separated into leaves (intact and partial) and root mass, dried at 60°C for at least 2 days, and then weighed. Seagrass cover was also calculated for each intertidal stratum at each site by measuring the percent cover in a 1 m^2 quadrat. A total of 20 random quadrats were measured in each stratum, and the mean calculated.

Statistical Analyses

Total invertebrate abundance ($ind.m^{-2}$) and diversity (species $richness.core^{-1}$) were initially analysed using a three-way analysis of variance (ANOVA) to determine whether any differences were present among sites, and tidal strata among seasons. As there were no replicates for strata within the invertebrate biomass data, a two-way ANOVA was used to determine differences among sites and seasons. If an ANOVA indicated any significant differences at treatment levels, a post-hoc Tukey test was used to determine pair-wise differences.

Differences in invertebrate assemblage were investigated with the Bray-Curtis similarity matrix. Non-parametric multi-dimensional scale (nMDS) ordination plots were used to display differences in invertebrate assemblages between sites and tidal levels (Clarke & Warwick, 2001), and analysis of similarity (ANOSIM) was used to determine whether any observed differences were statistically significant. The contribution of specific taxa to the differences in community assemblages among sites was examined using SIMPER analysis (similarity percentage-species contribution) (Clarke & Warwick, 2001). Pearson correlation was used to test whether there were statistically significant relationships between seagrass mass and invertebrate diversity, abundance or biomass. Spearman rank correlation was used to test for relationships among invertebrate abundance, diversity or biomass and mean sediment size, organic carbon content and mean percent seagrass cover. All data were tested for normality and homogeneity of variance. Abundance and biomass data were normalised via log transformations, and alpha (α) was set at 0.05.

Results

Environmental variables

With the exception of WB, all sites consisted predominately of fine sand (>85%) with the mean sediment size between 2-3 on the phi (**Φ**) scale (Table 1). WB was mostly made up of medium sand (1-2 **Φ**), although the low intertidal stratum was classified as fine sand. Organic carbon content of the sediments showed no consistent pattern among the tidal strata at each site.

Table 1. Environmental characteristics of the study sites. (± SD)

Site	Tidal strata	Mean Sediment particle size (Φ)	% organic carbon	Mean % vegetation cover	Mean mass of seagrass leaves (gDW)	Mean mass of seagrass roots (gDW)
East Inlet	High	2 47 ± 0 35	1 18	0	0.01 ± 0.04	0.04 ± 0.13
	Mid	2.43 ± 0.46	2 22	51.5 ± 43.08	0.41 ± 0.47	1.59 ± 1.93
	Low	2 42 ± 0.44	3.14	2.5 ± 7.86	0.01 ± 0.07	0.02 ± 0.11
Robbins Passage	High	2 50 ± 0.32	0.95	34.5 ± 41.78	0.16 ± 0.31	1.03 ± 0.90
	Mid	2.46 ± 0.34	1.17	76 0 ± 23.26	0.50 ± 0.52	1.71 ± 0 99
	Low	2.47 ± 0.32	0.94	27.5 ± 38.92	0 06 ± 0.10	0.27 ± 0.40
Shipwreck Point	High	2.47 ± 0.36	2.70	19.0 ± 29.23	0.09 ± 0.16	1.06 ± 2.00
	Mid	2.42 ± 0.46	1.51	84.5 ± 15.55	0.49 ± 0.59	4.95 ± 3.37
	Low	2.43 ± 0.45	2.74	11.75 ± 25.72	0.07 ± 0.14	0.69 ± 1.47
West Beach	High	1.60 ± 1.20	2.90	63.5 ± 40.69	0.13 ± 0.18	0 81 ± 1.19
	Mid	1.83 ± 0.78	2.31	13 0 ± 28.67	0	0
	Low	2.08 ± 0.67	1 97	2.5 ± 9.10	0	0

Seagrass cover varied at each of the four sites, as did seagrass mass, with SP and RP having the greatest total amounts, and WB the least. The mid-intertidal stratum had the greatest cover and mass at EI, RP and SP, while the high intertidal stratum had the greatest cover and mass of seagrass at WB (Table 1). All the sites had some seagrass present in each of the intertidal strata. Pearson correlation showed a strong relationship between percent seagrass cover and seagrass leaves and seagrass roots biomass ($r^2 = 0.89$ and 0.79, respectively). The three-way ANOVA showed that tidal level had a significant effect on seagrass leaves and seagrass roots biomass with a significant interaction between site and tidal level, although there was no seasonal effect (Table 2).

Table 2. Results of three-way ANOVAs (fixed factor: tidal level, random factor: season and site) using dry weight of seagrass from the three different tidal levels at each of the four sites over the five sampling periods.

Factor	d.f.	Seagrass leaves				Seagrass roots			
		SS	MS	F	P	SS	MS	F	P
Tidal level	2	11.12	5.5	5.4	**0.041**	353 7	176.8	2 9	0.129
Season	4	0.3	0.09	0.6	0 659	2.4	0 6	0.2	0.874
Site	3	3 4	1 1	1.1	0.393	334.5	111.5	1.8	0.236
Tidal level*Season	8	1.1	0.1	1 5	0.205	26.8	3.3	1.1	0.372
Tidal level*Site	6	5.8	0.9	10.4	**<0.001**	361.1	60.1	20.5	**<0.001**
Season*Site	12	1.1	0.09	1.0	0 447	21.4	1.7	0 6	0.814
Tidal level*Season*Site	24	2.2	0.09	1.1	0.336	70.4	2.9	1.4	0.073
Error	540	45.5	0.08			1083	2.0		

Invertebrate abundance and diversity

A total of 28,928 animals from 35 taxa were collected during the sampling period, with 11 taxa making up 90% of the total abundance (Appendix 1). Bivalves and gastropods dominated the assemblage (44% and 35% of total individuals, respectively), while amphipods and polychaetes made up 3% and 6% of the total individuals, respectively. The most abundant bivalve was *Paphies elongata* (27%). The mean number of individuals of all taxa at all sites was 6026.6ind.m^{-2}, with the highest density of animals collected at the mid-intertidal stratum at SP in January 2005 (94,125ind.m^{-2}), and the lowest density from the high intertidal stratum at RP in January 2006 (no animals found). The number of taxa per core ranged from 0 to 13, with a mean of 5.5 taxa per core.

There was variation, but no consistent pattern, in invertebrate abundance with tidal level, season and site (Table 3). Tidal level and season both had an effect on invertebrate abundance, but there was also a significant interaction between tidal level and site, and tidal level, site and season. The mid-intertidal strata had the greatest mean density of invertebrates at all sites over the sampling period, except at WB, where the low intertidal stratum dominated (Fig. 2). SP had the highest mean invertebrate density for each sampling period, while WB had the lowest, except in July, when EI had the highest and RP had the lowest. The total abundance at each site showed a decrease over the 12-month sampling period, with numbers decreasing steadily over that time.

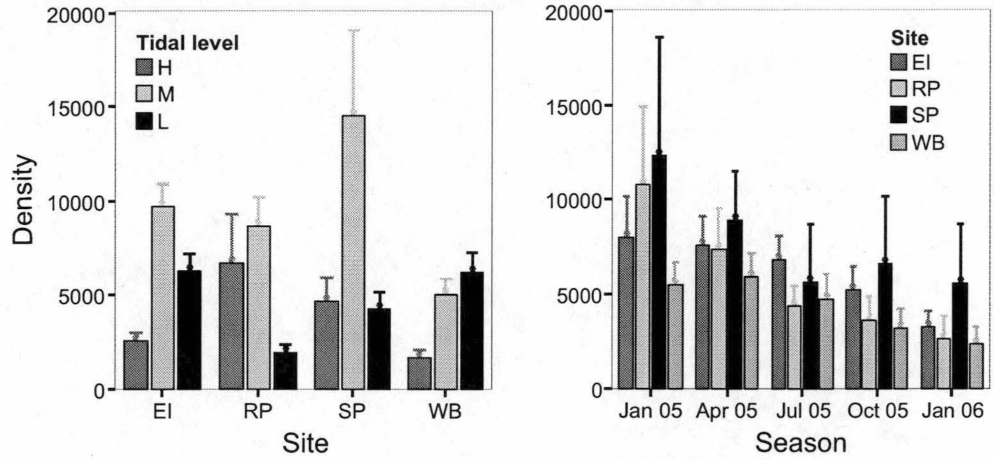

Figure 2. Mean (± S.E.) number of individuals per m^{-2} within each tidal stratum at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period and mean (± S.E.) number of individuals per m^{-2} for each site during each season.

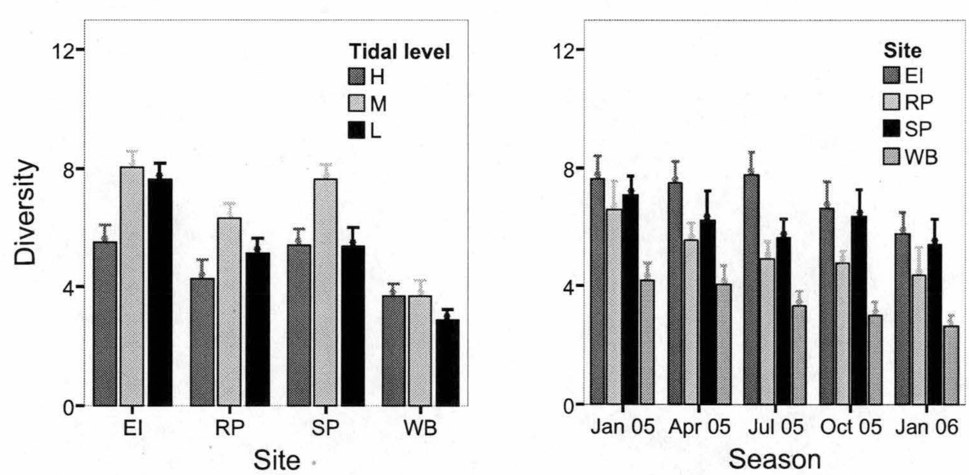

Figure 3. Mean (± S.E.) number of species per core within each tidal stratum at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period and mean (± S.E.) number of species per core for each site during each season.

Invertebrate diversity also showed a significant interaction between tidal level, site and season when analysed using a three-way ANOVA, with the number of taxa influenced by tidal level, season and site (Table 3). Except for WB, more taxa were found at the mid-intertidal strata, than the high and low intertidal strata, and at EI, rather than SP, RP and WB (Fig. 3).

No single taxon dominated at all sites. *P. elongata* dominated the mid- and low intertidal strata at EI and WB, while gastropods, polychaetes and nemerteans were more prevalent in the mid- and high intertidal strata at SP and RP (Appendix 1). Mytilidae sp. were only present in substantial numbers at SP, which also had the greatest number of the bivalve, *Katelysia* sp. and the soldier crab, *Mictyris platycheles*. Polychaetes were more prevalent at RP and SP, while amphipods and isopods were present at all four sites.

Table 3. Results of three-way ANOVAs (fixed factor: tidal level, random factor: season and site) using invertebrate abundance and diversity from the three different tidal levels at each of the four sites over the five sampling periods.

Factor	d.f.	Abundance				Diversity			
		SS	MS	F	P	SS	MS	F	P
Tidal level	2	22.3	11.1	5.2	0.050	302.2	151.1	4.6	0 054
Season	4	18.2	4.5	39.9	**0.030**	222.9	55.7	7.0	**0.027**
Site	3	4.1	1.3	0.6	0.613	1073.9	357.9	12.3	**0.007**
Tidal level*Season	8	1.3	0.1	0.8	0.600	68.6	8.5	1.5	0.182
Tidal level*Site	6	12.9	2.1	10.6	**<0.001**	178.0	29.6	5.4	**0.001**
Season*Site	12	1.8	0.1	0 7	0 688	57 0	4.7	0.8	0 579
Tidal level*Season*Site	24	4.8	0.2	2.9	**<0.001**	130.0	5.4	1.9	**0.004**
Error	540	37.0	0.06			1482	2.7		

Biomass

The total biomass of individuals from all sites was 1668.5gDW.m^{-2} (mean = 27.1gDW.m^{-2}), with EI having the greatest total amount (903.4gDW.m^{-2}). A two-way ANOVA showed that site explained some variation in invertebrate biomass (Table 4), and Tukey tests indicated that EI (mean = 1.60) and SP (1.39) had significantly greater biomass than did WB (0.99) and RP (0.97). The low intertidal stratum had the greatest biomass at each site over all the sampling periods, except for RP, where the mid-intertidal stratum had the greatest biomass (Fig. 4). Invertebrate biomass fluctuated slightly over the five sampling periods, but this was not statistically significant.

Table 4. Results of two-way ANOVAs (random factor: season and site) using invertebrate biomass from the four sites over the five sampling periods.

Factor	d.f.	SS	MS	F	P
Season	4	0.4	0.1	2.8	0.070
Site	3	4.2	1.4	36.0	**<0.001**
Season*Site	12	0.4	0.03	0.2	0.986
Error	40	5.2	0.1		

The biomass size distribution for the 11 taxa over the whole sampling period are presented in Appendix 2. It is clear that the high biomass at EI was due to the two *Paphies* species (*P. elongata* and *Paphies* sp.) and crabs (46% and 26.5% of biomass, respectively), with 96% of the *Paphies* spp. biomass in the second largest size class (8-20mm). Gastropods and other bivalves also made up a large proportion of the biomass for each site, especially for SP. SP had the majority (41.6%) of the gastropods in the 4mm size class, with high numbers in the 8-20mm (32.3%) and 1mm (24%) size classes. RP followed a similar trend, but had a larger proportion of small gastropods than at SP (34% in 1mm size class). While RP and SP had the greatest abundance of bivalves, SP and EI had the greatest biomass, indicating that while EI may have had fewer bivalves than RP, they were bigger. Polychaetes were most prevalent in the medium size range at all sites except WB, with EI having the greatest mass of polychaetes, while RP had the highest proportion (17% of the total biomass). SP and WB had similar numbers of worms but SP had the greatest biomass, mostly in the larger size class, indicating that WB had many small worms, while SP had many large worms. SP had the greatest total biomass of isopods, with the 2mm size class having the highest biomass at each site. RP had the greatest total biomass of amphipods, with the majority in the 2mm size class. EI had 79% of its total amphipod biomass in the 1mm size class, while the other sites had the majority of their amphipod biomass in the 2mm or 4mm size classes.

Community composition

Multivariate ordination (nMDS) showed that macroinvertebrate community composition differed among sites (Fig. 5). A two-way ANOSIM verified that the difference in community composition was statistically significant among all sites (global $R = 0.855$, $p < 0.001$) and all strata levels (global $R = 0.633$, $p < 0.001$). To reduce the risk of a Type 1 error, the Bonferroni correction was applied to adjust the alpha level to 0.0834 and 0.0167 for each of these comparisons, respectively, but the differences remained significant.

The taxa contributing to the dissimilarity between the four sites were identified through SIMPER analysis. The major differences were that SP and RP both had higher numbers of gastropods and polychaetes compared to EI and WB (contributing 4-14% to dissimilarity), while EI and WB had a greater abundance of *P. elongata* of which SP and RP had extremely low numbers (contributing 14-16% to dissimilarity). EI and WB differed mainly through the fact that EI had a greater number of *Katylesia* sp., isopods and gastropods than did WB. RP and SP were the most similar sites, but they differed predominately in that SP had an abundance of Mytilidae sp., and a higher abundance of *Mictyris platycheles*, while RP had a higher abundance of gastropods.

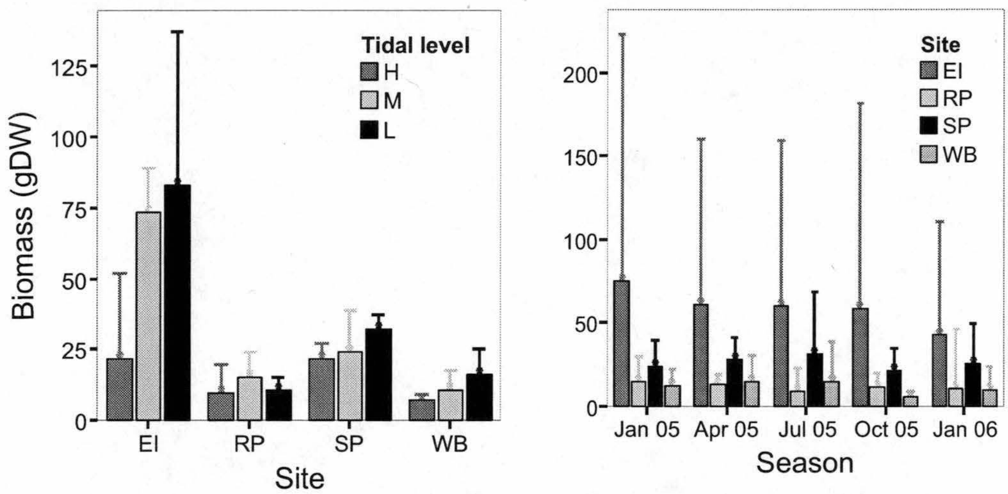

Figure 4. Mean (± S.E.) biomass of animals per m^{-2} within each tidal stratum at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period and mean (± S.E.) biomass per m^{-2} for each site during each season.

Macroinvertebrate community composition also varied among tidal zones at each site (Fig. 6). The community compositions at EI and SP were well separated along the intertidal strata, as the ANOSIM confirms (global R = 0.737 and 0.786, respectively), while at RP and WB the communities were separated among tidal zones, but showed some overlap in invertebrate assemblages (global R = 0.516 and 0.493, respectively). At EI, the high intertidal stratum differed from the low and mid-strata due primarily to the abundance of the amphipod *Urohaustorius halei* and very low numbers of *Katelysia* sp., gastropods and anthozoans, while the mid- and low strata differed due to the abundance of gastropods, the isopod Sphaeromatidae unid.

and *Katelysia* sp. and low numbers of Cumacea sp. at the mid-intertidal stratum, compared to the low intertidal stratum. At SP, gastropods and the polychaete *Olganereis edmondsii* were prevalent at the high and mid-strata, but not at the low intertidal stratum, with the mid-stratum being the only area with Mytilidae sp.. RP had a similar pattern, with gastropods present in high numbers at the high and mid-intertidal strata, but not at the low stratum, while the low stratum had a greater number of *U. halei* than the other strata. At WB, the high and low intertidal strata showed the greatest difference in community assemblages, with the low stratum characterised by *P. elongata*, and the high by *Katelysia* sp. This was also the primary cause of separation between the high and mid-strata, as demonstrated by the ANOSIM.

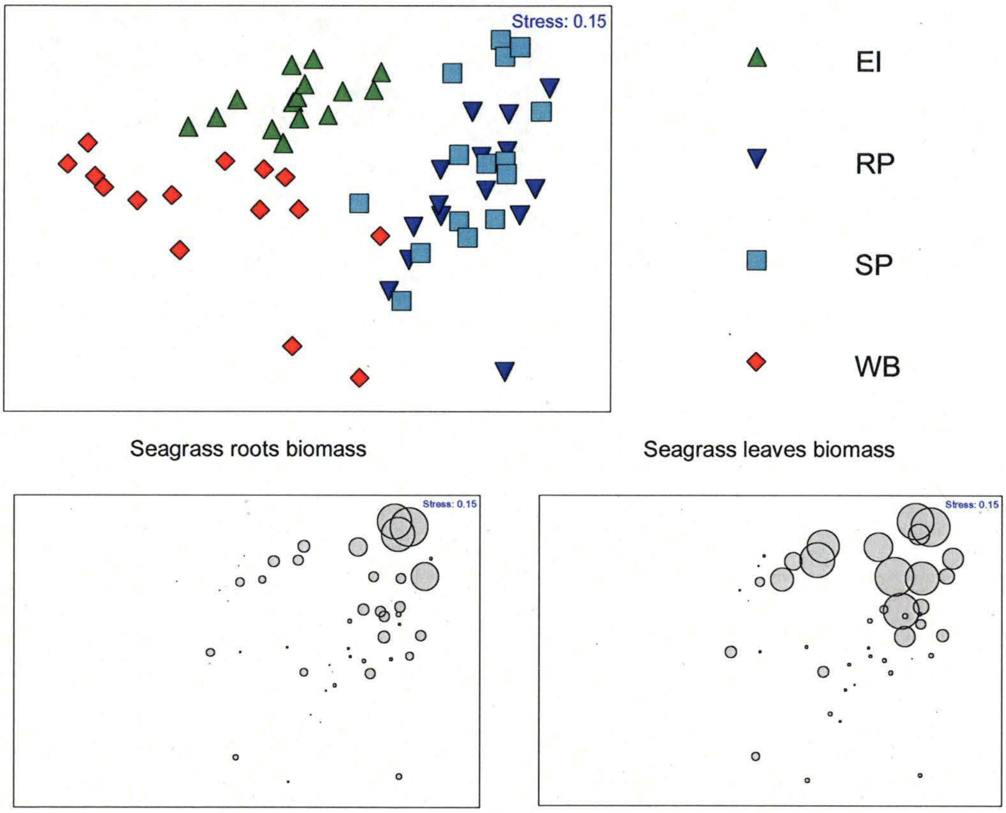

Figure 5. nMDS ordination showing macroinvertebrate assemblages at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach), over the 5 sampling seasons and tidal levels, with bubble plots of dry mass of seagrass roots and seagrass leaves superimposed.

Effect of environmental variables on invertebrates

Of the environmental variables measured, seagrass was the only variable that was collected on the same occasions as the invertebrate sampling. The other environmental variables, sediment particle size, % organic carbon and % seagrass cover, were only measured on one occasion, rather than at each of the five sampling periods. The variation in abundance of invertebrates among sites is partially related to seagrass biomass, i.e. dry mass of seagrass leaves, seagrass roots and total seagrass mass (Table 5). Invertebrate diversity is also positively correlated with seagrass biomass. The remaining variables showed no correlation with invertebrate diversity or abundance. The lack of correlation between invertebrates and seagrass cover despite the relationship with seagrass mass, may be due to spatial differences in scale, as % seagrass cover could only be applied to the whole intertidal stratum, while the seagrass mass was specific for each core collected. Invertebrate biomass showed no correlation with the percent of organic carbon in the sediment, mean sediment particle size, % seagrass cover or seagrass mass.

Table 5. Pearson correlations between seagrass biomass and invertebrate abundance, diversity and biomass.

	Seagrass leaves (gDW)	Seagrass roots (gDW)	Total seagrass (gDW)
Abundance.m^{-2}	0 530*	0.473*	0 496*
Species	0.548*	0.474*	0.499*
Biomass	0.202	0 073	0.092

* correlation is significant at the 0.01 level

The environmental variables were superimposed as bubble plots onto the invertebrate abundance ordination (Figs. 5 & 7). Seagrass root and seagrass leaves biomass both appeared to increase along the main MDS axis, and explained the clustering in the top right hand corner of the plot, but seagrass biomass did not explain all of the division among the sites. Mean sediment particle size increased slightly along the MDS axis and may have partly explained the different community assemblage at WB. The remaining variables, percent organic carbon and percent seagrass cover, appeared to show no pattern on the MDS plot. When seagrass biomass was superimposed over the MDS plots for each site, the differences in community assemblages among intertidal zones appeared to be driven to some extent by seagrass biomass (Fig. 6).

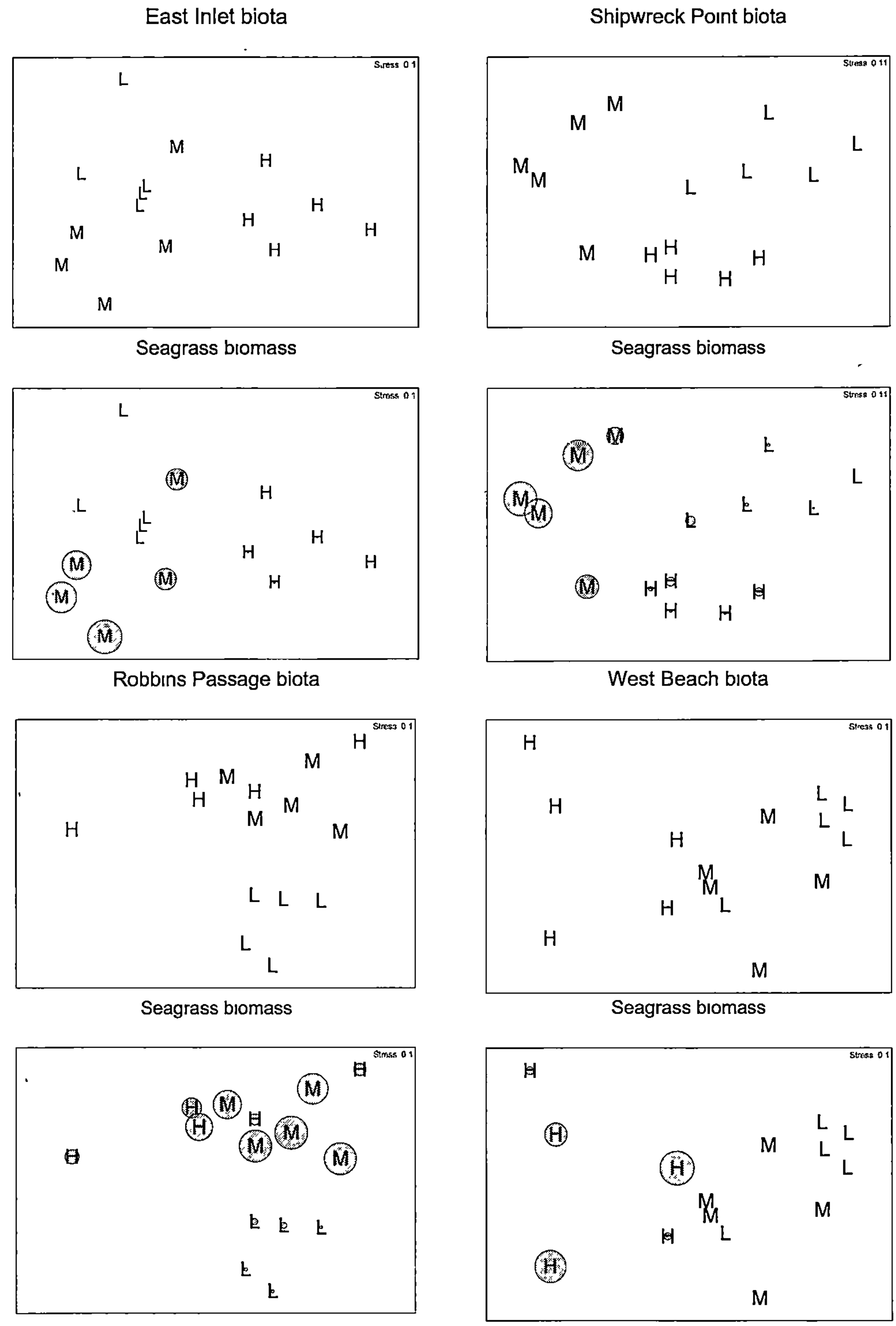

Figure 6. nMDS ordination showing macroinvertebrate assemblages at the three tidal levels (H: High, M: Mid, L: Low) at each site in the Robbins Passage/Boullanger Bay wetlands, Tasmania, over the 5 sampling seasons, with bubble plots of dry mass of seagrass superimposed.

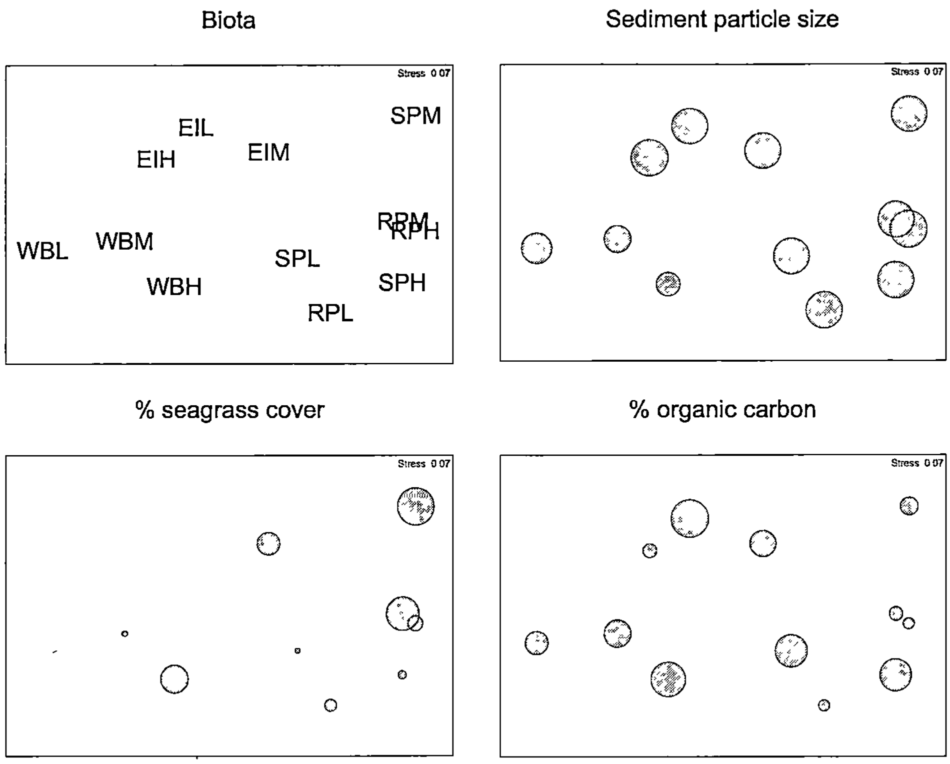

Figure 7. nMDS of invertebrate abundance data at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach, H: High, M: Mid, L: Low), averaged over the five sampling periods. The same MDS with superimposed circles of increasing size with decreasing mean sediment particle size, increasing sediment concentration of organic carbon, % seagrass cover.

Discussion

Spatial variation

The study sites differed in their macroinvertebrate abundances, diversities, biomasses and community compositions. EI had the greatest number of species and greatest biomass, while SP had the greatest number of individuals. WB and RP had the lowest and second lowest number of individuals and species, and WB the lowest biomass. Various factors may have contributed to these differences. Sediment composition is an important factor in determining the structure of macroinvertebrate assemblages (Kalejta & Hockey, 1991; Moverley & Jordan, 1996; Ysebaert & Herman, 2002; Silva *et al.*, 2006). Macroinvertebrate community composition varied significantly among all the study sites (Fig. 5) and sediment size variation may have explained some of the difference in community composition between WB and the remaining three sites (Fig. 7), however Edgar *et al.* (1999b) found that sediment size did not strongly influence invertebrate community composition in Tasmanian estuaries. Sediment composition also influences invertebrate abundance and biomass, although this effect may not be consistent (Dankers & Beukema, 1981; Edgar *et al.*, 1999b). The sites sampled in this study did not cover a wide range of sediment types; three sites (SP, RP and EI) had similar Φ values for mean grain size, while WB had lower values, i.e. coarser sediment, reflecting the fact that WB was the most exposed site, even though it was still classified as a dissipative beach (F. Spruzen pers. obs.). Despite this slight variation there was no significant correlation between invertebrate abundance, diversity or biomass and sediment grain size.

Sediment size and organic carbon content are generally correlated, as the smaller grain size and interstitial spaces, result in increased retention of organic matter (Peterson, 1991; Silva *et al.*, 2006). The absence of significant correlation between % organic carbon and macroinvertebrate abundance, diversity or biomass in this study once again probably reflects the small range in sediment size.

Sea grass abundance remains as a possible explanatory variable; seagrass cover did vary among sites, but there was no correlation with invertebrate abundance, diversity or biomass at any of the sites. The dry mass of seagrass leaves and roots (seagrass biomass) gives a more precise and localised measure of seagrass abundance. Seagrass biomass correlated positively with invertebrate abundance and diversity, as in a number of other studies (Stoner, 1980; Castel *et al.*, 1989; Edgar *et al.*, 1994; Heck *et al.*, 1995; Edgar & Barrett, 2002). The benefits of a seagrass canopy seem obvious: it provides refuge or cover from predators, shelter from extreme environmental conditions, delayed desiccation during low tides, a substrate for food growth in the form of algae, and habitat heterogeneity (Lewis & Stoner, 1983; Castel *et al.*, 1989; Lee *et al.*, 2001).

The benefits of the seagrass root mass are not as clear. Stoner (1980) found that infauna abundance decreased in vegetated sites and attributed this to the inhibition of tube building or burrowing due to the rhizome mats in the seagrass beds (Stoner, 1980). Lee *et al.* (2001) and Castel *et al.* (1989) found the reverse to be true, and suggested that the rhizome mats offer protection and provide food for the infauna. In this study seagrass leaf biomass had a slightly stronger correlation with abundance and diversity than root biomass, although both were significant (Table 5).

Seagrass biomass has also been related to community composition (Attrill *et al.*, 2000), with a study by Edgar *et al.* (1994) concluding that community composition in Westernport Bay, Victoria, showed a partial separation based on the presence or absence of seagrass beds. In the present study, seagrass biomass explained some of the variation in community assemblages among the sites and tidal levels (Figs. 5 & 6). RP and SP, sites with the highest biomass of seagrass, had communities dominated by gastropods and annelids, while EI and WB were dominated by *P. elongata*, a filter feeder. A number of studies have also found higher invertebrate biomass and production in vegetated areas as compared to unvegetated (Edgar *et al.*, 1994; Heck *et al.*, 1995), but this was not the case here, as invertebrate biomass showed no overall correlation with seagrass biomass, perhaps because of the prevalence of bivalves at some sites, which heavily influenced the biomass totals.

Tidal level had a significant effect on invertebrate abundance and species richness, with the highest values of both found in the mid-intertidal stratum, while the low intertidal stratum typically had the greatest biomass. A similar pattern was found by (Dankers & Beukema, 1981) in the Wadden Sea, but Edgar and Barrett (2002) found that in Tasmanian estuaries the number of species and abundance continued to increase as they moved down shore to 0.7m below low water mark. Honkoop *et al.* (2006) found greater numbers of individuals and species at lower tidal levels in north-western Australia, and Boehs *et al.* (2004) found that molluscs decreased in abundance and diversity at higher tidal levels, i.e. between mid- and high tide. The peak in invertebrate abundance and diversity at the mid-intertidal stratum in the present study may reflect the higher density of seagrass cover and biomass in this zone at three of the four study sites.

Although a decrease in invertebrate abundance and diversity at higher tidal levels might be expected, simply on the basis of exposure, this would be alleviated by the high seagrass biomass at the mid-intertidal stratum, due to the shelter from high temperatures, desiccation and predators, as well as retained moisture (Castel *et al.*, 1989; Lee *et al.*, 2001). Seagrass also creates a more complex environment, leading to increased diversity (Rainer, 1981). Invertebrate community assemblages were partially influenced by tidal level, although this too could be influenced by seagrass biomass. Honkoop *et al.* (2006) found that benthic assemblages differed among tidal heights along 80 Mile Beach in north-western Australia, although this effect was not consistent along the shore, confirming that tidal level is not solely responsible in determining invertebrate community composition.

Edgar and Barrett (2002) also found that invertebrate biomass increased down shore in Tasmanian estuaries, as did Beukema (1981), although an earlier study

(Beukema, 1976) found that invertebrate diversity and biomass in the Wadden Sea followed an almost bell-shaped curve, with peak invertebrate numbers around the mid-tidal level. Although increased submersion allows the fauna to feed for longer, and provides protection from predation by birds (Peterson, 1991), submerged invertebrates are also vulnerable to predation from fish for a longer time period, but this may be outweighed by the benefits mentioned above.

Temporal variation

Temporal variation in a patchy and heterogeneous environment such as tidal flats is very hard to quantify, and may be confounded by fine-scale (e.g. daily) variations (Morrisey *et al.*, 1992). Various studies have reported seasonal effects in invertebrate abundance and biomass, but of varying magnitudes (Moore, 1978; Reise, 1985; Kalejta & Hockey, 1991). Seasonal variation in invertebrate abundance is generally the result of recruitment events, which can be detected by using a 0.5mm sieve size or smaller (Edgar *et al.*, 1999a). Seasonal variation was not the primary focus of the present study, and recruitment events may not have been sampled appropriately with a 1mm sieve size. The gradual decrease in invertebrate abundance and diversity over the study period could have been caused by the high rainfall in October 2005 (136mm compared to long-term mean of 100mm), resulting in increased freshwater runoff or sediment into the wetlands, reducing recruitment and survival. Further studies and a more long-term data set would be needed before any statements could be made about the stability or seasonal patterns of the invertebrate population in the wetlands.

Comparisons to other sites

Since the Robbins Passage/Boullanger Bay wetlands are the most important shorebird area in Tasmania, it is important to try to compare them with other sites, especially in Australia, despite the difficulties arising from different sampling techniques and sieve sizes. In general, the Robbins Passage/Boullanger Bay wetlands, with mean total abundance of 6000ind.m^{-2} and biomass of 27gDW.m^{-2} seem to compare favourably with other temperate Australian sites (Table 6). Edgar *et al.* (1999a) sampled macroinvertebrates in estuaries around Tasmania in the late 1990s, including the Robbins Passage/Boullanger Bay wetlands, and found mean biomass to be 13.7gAFDW.m^{-2} and abundance 4474.2ind.m^{-2}, which are comparable to the present study, even though they used ash-free dry weight (AFDW) as biomass measure while we used dry weight (DW). Dorsey (1982) found an extremely high invertebrate abundance at Werribee, in Victoria, as the study area was adjacent to a sewage farm, and the sampling sites were situated between two drains.

Table 6. Macroinvertebrate abundance and biomass and shorebird densities found at other tidal flats.

Location	Lat.	Invertebrate abundance (ind.m^{-2})	Invertebrate biomass (gDW.m^{-2})	Sieve size (mm)	Shorebird abundance (birds.ha^{-1})	Reference
The Wash, England	53N		11-32*	0.5	4 8	(Goss-Custard, 1977; Goss-Custard & Yates, 1992)
Wadden Sea, Holland	53N		26 6*	1.0	3.4	(Beukema, 1981; Wolff, 1991)
Tagus estuary, Portugal	38N	11,780	200-1100#	0.5	10 8	(Moreira, 1999; Rodrigues *et al.*, 2006)
Bay of Cadiz, Spain	36N		37-53*	0.5	100	(Masero *et al.*, 1999)
Banc d'Arguin, Mauritania	19N		17*	0.6	41.6	(Wolff, 1991; Wolff *et al.*, 1993)
Hinchinbrook Is, Nth QLD	18S	791		1.0		(Dittman, 2002b)
Roebuck Bay, NW WA	18S	1017	15.53*	0.5	3.45[c]	(Tulp & de Goeij, 1994)
Bay of Rest, NW WA	18S	992	4.06	1.0		(Wells, 1983)
Berg River estuary, South Africa	32S	17,322-89,416	19.35	0.5	56.7	(Kalejta & Hockey, 1991; Velasquez *et al.*, 1991)
Coorong, SA	35S	1337		0 5	6.1[b]	(Paton *et al.*, 2001)
Werribee, VIC	38S	140,000 –400,000		0.5		(Dorsey, 1982)
Westernport Bay, VIC	38S		1.55-43.1*	1.0	0.34[a]	(Edgar *et al.*, 1994)
NW TAS	40S	2505.8 - 8654.1	13.7-587*	1.0		(Edgar *et al.*, 1999a)
NW TAS	40S	6026.6	27.1	1.0	1.1-5 2	This study

* biomass measured as gAFDW. m^{-2}
# biomass measured as wet weight. m^{-2}
[a] calculated from (Dann, 1999a)
[b] calculated from (Paton *et al.*, 2001)
[c] calculated from (Rogers, 1999)

Tropical intertidal flats typically have a greater diversity, but lower abundance of invertebrates than temperate sites (Dittman, 2002a). The lower abundance of invertebrates can be seen from studies in north Queensland (Dittman, 2002b) and northwest Western Australia (Wells, 1983; Tulp & de Goeij, 1994), although biomass at the Western Australian sites was relatively high. Other tropical tidal flats, such as Banc d'Arguin in western Africa, also have a high invertebrate biomass, and very high shorebird densities (van de Kam et al., 2004). Temperate regions such as the Wadden Sea in Europe, one of the largest intertidal areas in the world, has a higher invertebrate biomass, but a much lower shorebird density, comparable to densities in northwest Western Australia and Tasmania. Overall, it appears that the temperate regions have a higher invertebrate biomass, but a lower shorebird density than the tropical intertidal areas. However, invertebrate biomass may not necessarily be a good guide to the availability of shorebird food over time, since productivity and biomass are not necessarily related. The high biomass values may also be composed of invertebrates that are not shorebird prey, or not harvestable by shorebirds. Many other biotic and abiotic factors may influence shorebird use and habitat suitability of the tidal flats, such as seagrass cover, sediment composition and even wind speed.

Conclusion

It is clear that the environmental variables acting on tidal flats are interrelated, making it difficult to separate any particular one as the primary cause of variation in invertebrate abundance, biomass and/or composition. Seagrass aids in the accumulation of fine sediments which leads to increased organic nutrients and carbon (Dankers & Beukema, 1981). High tidal strata usually have coarser sediments than low tidal strata, and in the present study, the mid-tidal stratum is dominated by seagrass beds at three of the study sites, adding to the complexity of the interactions. Each area is unique and they are not all influenced by the same combination of variables, so the four variables measured in this study could not explain all of the variation in invertebrate abundance, biomass and composition among the sites. Other studies have included variables such as salinity, tidal range and elevation (inundation time) (Wolff *et al.*, 1993; Edgar *et al.*, 1999b; Rodrigues *et al.*, 2006), and have successfully explained some of the variation in invertebrate distribution and composition throughout estuaries, and on larger geographical scales. Current velocity could also be considered; however, there is likely to be a high degree of covariance among variables, such as inundation time and tidal level, and it will be difficult to separate their effects.

The abundance and biomass of intertidal invertebrates is a vital component in the determination of suitable shorebird habitat. This work is a component of a larger study to determine shorebird feeding preferences within the Robbins Passage/Boullanger Bay wetlands by quantifying the amount and type of food available to the birds. In comparison with other shorebird sites, Robbins Passage/Boullanger Bay wetlands appear to have an adequate food supply for shorebirds, although it is not consistent throughout the area. Densities of feeding shorebirds are linked to prey availability (Goss-Custard *et al.*, 1977c), and the highest shorebird densities of 5.2 and 3.7birds.ha^{-1} are found at the two sites with the greatest invertebrate biomass and abundance, SP and EI (Spruzen *et al.*, 2008). Whether these are the primary considerations for shorebird habitat choice will be investigated in further studies.

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Appendix 1: Mean number of individuals.m^{-2} of each taxa at each tidal stratum (H = High, M = Mid, L = Low) within the four study sites in the Robbins Passage/Boullanger Bay wetlands over all five sampling periods.

Taxonomic name	East Inlet			Robbins Passage			Shipwreck Point			West Beach		
	H	M	L	H	M	L	H	M	L	H	M	L
Polychaetes												
Euzonus sp.	2.5	20	2.5	25	80	92.5	67.5	2.5	10	0	2.5	0
Nephtys sp.	127.5	212.5	225	440	342.5	125	262.5	320	137.5	77.5	52.5	90
Olganereis edmondsi (Hartman, 1854)	67.5	82.5	15	177.5	312.5	62.5	290	280	80	57.5	30	5
Polychaete sp. A	7.5	37.5	20	30	42.5	12.5	7.5	15	20	0	17.5	0
Crustacea												
Phoxocephalidae unid.	17.5	92.5	167.5	90	80	20	62.5	167.5	17.5	25	10	7.5
Urohaustorius halei (Sheard, 1936)	312.5	125	40	0	27.5	240	0	5	45	15	27.5	40
Amphipod sp. A	45	100	37.5	27.5	160	40	25	60	50	12.5	12.5	7.5
Sphaeromatidae unid	52.5	152.5	20	65	122.5	102.5	107.5	160	117.5	42.5	37.5	0
Isopod sp. A	0	2.5	0	15	17.5	0	0	70	2.5	2.5	0	0
Isopod sp. B	0	0	2.5	7.5	0	0	0	10	0	0	0	0
Isopod sp. C	0	2.5	5	0	2.5	0	0	0	0	0	0	5
Isopod sp. D	0	0	0	0	0	0	0	5	0	0	0	0
Copepod spp	0	0	0	0	0	0	0	0	0	0	2.5	0
Cumacea sp A	5	30	127.5	30	2.5	2.5	27.5	22.5	10	5	5	0
Mysidae spp.	7.5	7.5	2.5	0	7.5	20	0	5	0	0	2.5	0
Ostracod spp.	0	0	0	0	0	0	0	2.5	0	0	2.5	0
Callianassidae unid.	0	2.5	0	0	2.5	0	0	17.5	2.5	0	0	5
Penaeidae unid.	5	5	2.5	22.5	22.5	12.5	0	0	0	2.5	2.5	5
Mictyris platycheles (H. Milne Edwards, 1852)	112.5	60	160	5	30	137.5	185	62.5	357.5	107.5	27.5	22.5
Grapsidae unid.	0	17.5	0	2.5	5	0	10	12.5	0	0	0	0
Philyra sp.	0	5	17.5	2.5	0	0	0	5	2.5	0	0	0
Cirripedia sp.	100	110	85	0	0	0	0	765	0	5	42.5	25
Molluscs												
Conidae unid.	0	20	12.5	2.5	5	2.5	5	10	22.5	0	0	0

Taxonomic name	East Inlet			Robbins Passage			Shipwreck Point			West Beach		
	H	M	L	H	M	L	H	M	L	H	M	L
Gastropod spp *	47.5	960	237.5	5137.5	6442.5	667.5	3112.5	7985	855	30	90	12.5
Maoricolpus sp.	0	0	0	7.5	2.5	0	0	0	0	0	0	0
Electroma georgiana (Quoy & Gaimard, 1834)	0	0	0	0	0	0	0	17.5	20	5	0	0
Katelysia sp.	35	1010	247.5	497.5	835	415	435	962.5	2322.5	660	115	247.5
Mytilidae sp.	0	5	0	2.5	5	2.5	47.5	3130	2.5	0	0	0
Paphies elongata (Reeve, 1854)	1365	4480	3510	20	7.5	5	0	7.5	37.5	517.5	4427.5	5642.5
Paphies sp.	2.5	75	5	10	15	17.5	2.5	25	22.5	25	27.5	2.5
Solenidae unid.	0	0	0	5	12.5	2.5	0	55	0	2.5	0	0
Nemertea unid.	20	42.5	35	77.5	50	5	17.5	342.5	95	87.5	122.5	105
Sipuncula unid	2.5	7.5	2.5	0	0	0	0	7.5	15	0	0	0
Holothuroidae unid	0	0	0	0	0	0	0	2.5	0	0	5	0
Anthozoa unid	240	2030	1290	2.5	12.5	0	0	20	7.5	12.5	2.5	7.5

*Gastropods were a combination of *Nassarius pauperatus* (Lamarck, 1822), *Hydrococcus brazieri* (T. Woods, 1876) and *Salinator fragilis* (Lamarck, 1822).

Appendix 2. Total biomass (gDW.m^{-2}) per size class of 11 major taxa at each site over all sampling periods and tidal strata.

Taxa	Size class					
	1mm	2mm	4mm	8-20mm	>20mm	Total
			East Inlet			
Amphipods	0 898	0.124	0.111	0.000	0.000	1.133
Bivalves	0.118	0.775	2.353	23.544	93.853	120.642
Crabs	0.033	0.558	2.110	225.360	12.041	240.101
Gastropods	0.846	0.374	12.286	8.956	0.000	22.463
Isopods	0.274	1.145	0.145	0.173	0.000	1.736
Mytilidae	0.000	0.015	0.000	0.000	0.000	0.015
Other crustaceans	0.140	0.014	0.795	6.598	0.000	7.546
Paphies spp.	0.241	0.961	12.804	400.068	1.193	415.267
Polychaetes	9.640	17.703	13.074	0.000	0.000	40.416
Shrimps	0.000	0.043	0.000	0.000	0.000	0.043
Worms	0.508	3.409	0.000	0.000	0.000	3.916
			Robbins Passage			
Amphipods	0.451	0.796	0.306	0.245	0.000	1.799
Bivalves	0.330	0.474	0.511	18.116	12.504	31.935
Crabs	0.000	0.031	1.638	68.313	27.625	97 606
Gastropods	10.445	1.548	12.714	5.934	0.000	30.640
Isopods	0.230	1.103	0.405	0.185	0.000	1.923
Mytilidae	0.004	0.000	0.205	0.225	0.000	0.434
Other crustaceans	0.029	0.056	0.041	0.000	0.000	0.126
Paphies spp.	0.081	0.028	0.040	0.040	0.000	0.189
Polychaetes	6.660	21.861	6.796	0.000	0.000	35.318
Shrimps	0.013	0.000	0.364	2.045	0.000	2.421
Worms	0.538	0.021	0.000	0.000	0.000	0.559
			Shipwreck Point			
Amphipods	0.354	0.343	0.763	0.000	0.000	1.459
Bivalves	0.263	0.779	14.728	101.255	53.797	170.820
Crabs	0.024	1.154	8.438	66.414	0.000	76.029
Gastropods	11.136	0.969	19.274	14.955	0.000	46.334
Isopods	0.428	2.025	0.215	0.000	0.000	2.668
Mytilidae	0.674	6.361	28.986	8.291	0.000	44.313
Other crustaceans	0.050	0.008	1.735	0.000	0.000	1.793
Paphies spp.	0.245	0 361	0.073	0.000	0.000	0.679
Polychaetes	6.239	11.664	6.113	0.000	0.000	24.015
Shrimps	0.006	0.000	0.206	0.000	0.000	0.213
Worms	3.433	7.020	8.758	0.000	0 000	19.210
			West Beach			
Amphipods	0.135	0.113	0.279	0.000	0.000	0.526
Bivalves	0.010	0.065	0.115	4.205	1.966	6.361
Crabs	0.020	0.010	1.741	19.488	0.000	21.259
Gastropods	0.015	0.318	3.409	2.989	0.000	6.730
Isopods	0.091	0.436	0.000	0.089	0.000	0.616
Mytilidae	0.000	0.000	0.000	0.000	0.000	0.000

Taxa	Size class					
	1mm	2mm	4mm	8-20mm	>20mm	Total
Other crustaceans	0.000	0.000	0.026	0.000	0.000	0.026
Paphies spp.	1.765	3.428	44.850	56.621	0.000	106.664
Polychaetes	2.998	7.556	15.076	0.000	0.000	25.630
Shrimps	0.000	0.070	0.000	0.000	0.000	0.070
Worms	0.000	2.050	0.094	0.000	0.000	2.144

(Polychaetes and Worms were classed as small (1mm class), medium (2mm class) and large (4mm class). Measurements based on width of animal; small <1mm, med = 1-3mm, large >3mm).

Chapter 3

Influence of environmental and prey variables on low tide shorebird habitat use within the Robbins Passage wetlands, Northwest Tasmania.

Abstract

Shorebirds feed primarily on tidal flats, and their distribution over these flats is influenced by their prey and abiotic factors. These factors act by influencing the distribution and abundance of the prey, or the shorebirds ability to exploit it. The aims of this study were to investigate the low tide foraging distribution of shorebirds at four sites within the Robbins Passage/Boullanger Bay wetlands, and the environmental and invertebrate factors that may influence their distribution. The greatest densities and number of shorebirds were found at Shipwreck Point and East Inlet. The shorebirds within-site distribution was also non-random, with the shorebirds present in greatest densities at the waters edge and low intertidal stratum, although this varied among species. Generally, on a small spatial scale, invertebrate diversity was positively correlated, and seagrass leaf mass was negatively correlated, with shorebird feeding density. On a large spatial scale, invertebrate biomass and seagrass root mass were positively correlated with shorebird feeding density. Invertebrate biomass and seagrass root mass explained 71% of the variance in total shorebird feeding density on the tidal flats. The variation in shorebird feeding density and diversity was therefore partly explained by invertebrate diversity and biomass, as well as the environmental factors seagrass roots and leaf mass and tidal flat area, although the strength of these relationships was influenced by the two different spatial scales of the study. The strength of the relationships between shorebird feeding density and the invertebrate and environmental variables was stronger on a large spatial scale. The presence of seagrass may have influenced shorebird feeding density by affecting the invertebrate abundance and composition or the shorebirds ability to detect and capture their prey. The area of the tidal flat had opposing effects on the shorebird species. These results can be used to assist in the development of management plans for the Robbins Passage/Boullanger Bay wetlands and the conservation of important shorebird areas.

Introduction

The ecology of shorebirds is strongly influenced by their food: its location, distribution, abundance and availability. Coastal wetlands and estuaries are places of patchy, but locally abundant prey, and shorebirds, migratory and resident, gather in these locations throughout the year. While the distribution and abundance of their prey predominantly determines the distribution of shorebirds on their feeding grounds (1977c; Bryant, 1979; Ribeiro *et al.*, 2004), other environmental factors, such as sediment particle size and composition (Yates *et al.*, 1993; Moreira, 1999) and vegetation cover (Zharikov & Skilleter, 2002) also play a role (Burger *et al.*, 1977; Kalejta & Hockey, 1994). In combination with biotic factors, these abiotic factors can influence the characteristics of the invertebrate prey, or the ability of the birds to exploit it.

Shorebird distributions on tidal flats have been studied extensively (Goss-Custard *et al.*, 1977b; Symonds *et al.*, 1984; Kalejta & Hockey, 1994), as have their feeding ecologies (Goss-Custard *et al.*, 1977a; Goss-Custard, 1985), and prey distributions (Bryant, 1979; Kalejta & Hockey, 1994). Australian researchers have recently begun studies in this area (Thompson, 1993; Dann, 1999a; Rogers, 1999), but as yet little research has been undertaken on habitat use by foraging shorebirds (Congdon & Catterall, 1994; Rohweder & Baverstock, 1996; Thompson, 1998; Finn *et al.*, 2007), and the only studies looking at the functional relationship between prey and shorebird distribution have so far been in Western Australia and New South Wales (Tulp & de Goeij, 1994; Rogers, 1999; Owner & Rohweder, 2003). With the exception of Rogers (1999), these studies have looked at only one or two species, while Tulp and Goeji (1994) focussed on diets and prey intake rates, rather than distribution, of great knots (*Calidris tenuirostris*) in relation to their prey. No comprehensive study on habitat use of mixed species assemblages has yet been conducted in Tasmania.

The Robbins Passage/Boullanger Bay wetlands in northwest Tasmania support the largest and most diverse community of migratory and resident shorebirds in Tasmania, with over 25,000 shorebirds present during the summer months, consisting of 23 different species (18 migratory, 5 resident) (Woehler & Park, 2006). Despite this importance, no studies have yet been conducted on shorebird habitat use in this wetland. We therefore investigated the low tide foraging distribution of shorebirds within the wetlands, and the factors that might influence their distribution. Two specific questions were addressed:

1. What are the spatial and temporal patterns of distribution of the shorebirds among the sites and over the tidal flat at each site?
2. Can the measured environmental and invertebrate variables be used to explain the variability in shorebird distributions within and among sites?

Method

Study area

The Robbins Passage/Boullanger Bay wetlands form a coastal intertidal system located in the far northwest of Tasmania (40° 40'S, 144° 50'E), with an area of over 100km^2 (Dunn, 2000). They consist of two large shallow tidal basins, Boullanger Bay and Big Bay, and smaller tidal areas, comprising Robbins Passage, Duck Bay and West and East Inlets, and the estuaries of three rivers: the Welcome, Montague, and Duck Rivers. The wetlands are an extensive area of tidal channels and intertidal sand flats, with a variety of habitats, including salt marsh, seagrass beds and open sand flats (Dunn, 2000). The area has a mean tidal range of 3.5m (Department of Primary Industries Water and Environment, 1999; BOM, 2005). The sand flats are the most dominant feature of the wetlands, comprising approximately 65% of the total site area (Dunn, 2000). The wetlands contain one of the most important areas of seagrass beds in Tasmania, dominated by *Posidonia australis*, with substantial areas of *Heterozostera tasmanica* and *Amphibolis antarctica* (Department of Primary Industries Water and Environment, 1999). The beds cover an area of approximately 8000 ha and are considered one of the largest seagrass areas in temperate Australia (Department of Primary Industries Water and Environment, 1999).

The Robbins Passage/Boullanger Bay wetlands regularly support more shorebirds than the rest of Tasmania combined (Woehler, 2007). They are a site of international significance for five migratory shorebird species: curlew sandpipers (*Calidris ferruginea*), double-banded plovers (*Charadrius bicinctus*), red-necked stints (*C. ruficollis*), red knot (*Calidris canutus*) and ruddy turnstones (*Arenaria interpres*), and of national importance for two resident species: pied (*Haematopus longirostris*) and sooty oystercatchers (*H. fuliginosus*) (Watts, 1999; WWF-Australia, 2004; Woehler, 2007). Recent land use changes in the wetlands catchments are potential factors threatening the shorebirds in the area.

Survey methods

The distribution and density (birds.ha^{-1}) of feeding shorebirds was investigated at low tide at four intertidal flats in the wetlands; East Inlet (EI), Robbins Passage (RP), Shipwreck Point (SP) and West Beach (WB) (Fig. 1). The sites were chosen to encompass a range of sediment types and vegetation cover, although the choice of sites was also influenced by accessibility, logistics and safety considerations. Between October 2004 and March 2006, the four sites were surveyed within an hour of predicted low tide twice a month during October to March and once a month April to September. All four sites were sampled within a 3 day period. Surveys were conducted during daylight, although some shorebird foraging occurs at night (Bibby *et al.*, 2000).

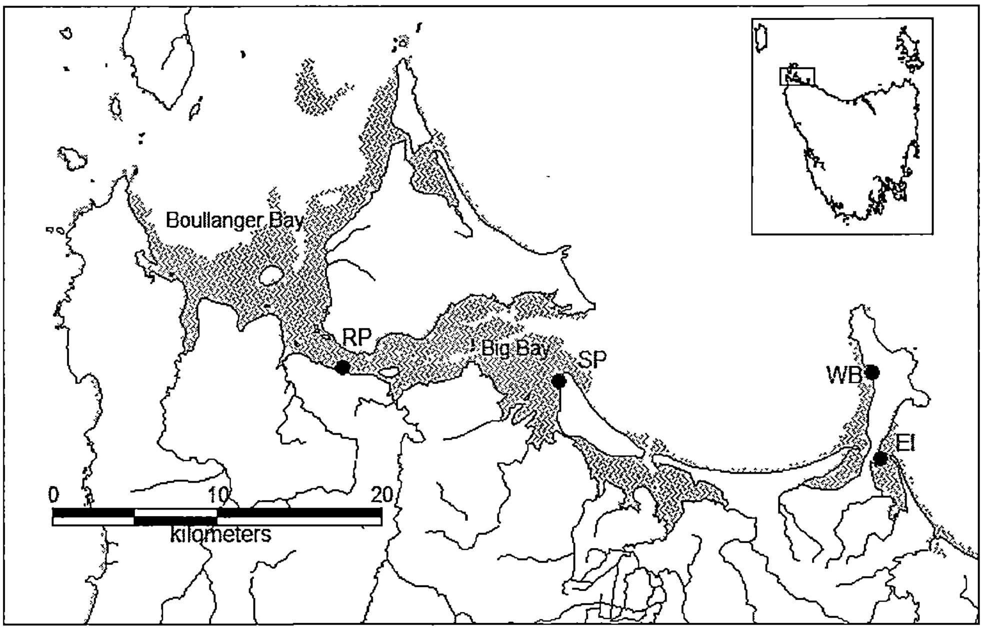

Figure 1. Map of northwest Tasmania showing the location of the four feeding sites in the Robbins Passage/Boullanger Bay wetlands. Stippled areas represent tidal flats. (EI = East Inlet, RP = Robbins Passage, SP = Shipwreck Point, WB = West Beach)

Each site consisted of a 400m long transect on the sand flat parallel to the shoreline, extending on each side from the high water mark to the low water mark. Due to the varying slopes at each of the feeding sites, the extent of the area exposed at low tide differed. The intertidal width of the feeding sites ranged between 400m and 600m, while the area of the sites ranged from 13-22ha. To determine whether the shorebirds displayed any preference for a particular section of the flats, each site was divided into 4 zones: high, mid and low intertidal strata, and the water's edge, which was defined as the narrow 1-2m strip between the low intertidal stratum and the open water, covered by a thin surface layer of water.

Each survey was conducted by walking the length of the transect parallel to the shoreline, equidistant between the high and low water mark and scanning the area up to 200m ahead with a 32x *Kowa* (TSN- 821) spotting scope to minimise disturbance to the birds (Altmann, 1974; Clarke & Warwick, 2001). Each bird was identified and counted and its location on the tidal flats recorded as high, mid, low intertidal strata or water's edge. The influence of the tide was standardised by conducting the surveys within a two-hour window around the low tide and only on low tides less than 1.3m (range = 0.7-1.3m).

Habitat and invertebrate sampling

The following habitat characteristics were measured at each feeding site: seagrass cover (%), seagrass biomass (g.Dry Weight (DW)), sediment particle size (phi (Φ) units), organic carbon content (%), tidal flat area (ha), and macroinvertebrate composition (species richness.core^{-1}), abundance (ind.m^{-2}) and biomass (gDW.m^{-2}). The sampling methods used and results obtained are detailed in Spruzen *et al.*(2007).

Statistical analysis

Analyses of shorebird distributions was limited to the eight commonest species: four residents and four migratory (Table 1). Total shorebird abundances and species diversity were initially analysed using a three-way analysis of variance (ANOVA) to determine whether there were any differences among sites, tidal strata and month. A post-hoc Tukey test was used to determine pair-wise differences if the ANOVA indicated any significant differences. Multi-way ANOVAs were also used to determine whether tidal strata or month was significant at each site.

A Bray-Curtis similarity matrix was used to examine differences in shorebird assemblages among sites, and a non-parametric multi-dimensional scale (nMDS) ordination plot was used to plot any differences. Analysis of similarity (ANOSIM) determined whether any observed differences were significant (Sergio & Bogliani, 2000; Sergio *et al.*, 2004). Habitat variables for each site were standardised and analysed using principal components analysis (PCA) to determine the main sources of variation among the four sites.

Table 1. Total abundance and frequency of occurrence of study species over the 18 month period and mean abundance (± SE).

Common name	Species name	Total no. of birds	Mean no. of birds (± SE)	Frequency n=116 (%)
Resident species				
Pied oystercatcher	*Haematopus longirostris*	855	4.96 ± 0.8	108 (93)
Sooty oystercatcher	*Haematopus fuliginosus*	206	0.91 ± 0.3	50 (43)
Red-capped plover	*Charadrius ruficapillus*	274	0.59 ± 0.2	58 (50)
Hooded plover	*Thinornis rubricollis*	56	0.18 ± 0.1	29 (25)
Migrant species				
Ruddy turnstone	*Arenaria interpres*	208	0.06 ± 0.1	13 (11)
Red-necked stint	*Calidris ruficollis*	1606	7.42 ± 2.4	45 (39)
Pacific golden plover	*Pluvialis fulva*	102	0.07 ± 0.1	8 (7)
Double-banded plover	*Charadrius bicinctus*	499	0.43 ± 0.2	28 (24)

Multiple stepwise regression was used to analyse the relationships among shorebird density and the environmental and invertebrate variables at two spatial scales: small scale, across the three intertidal strata at all four sites (12 sites total), and large scale, across the four sites only, over the 18-month period. Separate regressions were conducted for six shorebird density groups based on migratory status and feeding guild: 1) all shorebirds (all 8 study species), 2) migrant shorebirds (double-banded plover, Pacific golden plover, red-necked stint, ruddy turnstone), 3) Palaearctic shorebirds (Pacific golden plover, red-necked stint, ruddy turnstone), 4) resident shorebirds (hooded plover, pied oystercatcher, red-capped plover, sooty oystercatcher), 5) pecking shorebirds (hooded plover, red-capped plover, double-banded plover, Pacific golden plover, red-necked stint, ruddy turnstone) and 6) probing shorebirds (pied and sooty oystercatchers). Multiple stepwise regressions were also conducted for each of the eight study species individually.

To assist in the identification of variables that should be considered in the stepwise analysis, scatter plot matrices were used to identify linear relationships. To address the issue of collinearity among variables, pairs of strongly inter-correlated variables ($r > 0.6$) were considered as estimates of a single underlying factor, as in previous habitat selection studies (Pringle, 1987; Marchant & Higgins, 1993). The variable believed to be more important to the study organism was retained. The entry level for variables to be added to the regression model was 0.05 and the level at which they were removed was 0.1. The variables entered into the regression analyses for the six shorebird groups were selected from the six greatest eigenvectors from the PCA analysis that were not highly correlated. For the small scale analysis, these were invertebrate diversity, or invertebrate abundance and biomass, seagrass leaf mass, tidal flat area and sediment particle size. For the large scale analysis these were invertebrate diversity, or invertebrate abundance and biomass, seagrass leaf mass and seagrass roots mass. Invertebrate abundance and biomass were correlated with invertebrate diversity, therefore the regressions were calculated with invertebrate abundance and biomass, and then recalculated with invertebrate diversity, to identify the best regression model. The shorebird species regressions used the same habitat variables for the small scale analysis; seagrass leaf mass, sediment particle size and tidal flat area, and the biomass or abundance of their potential prey groups: amphipods, isopods, marine worms, gastropods, bivalves and *Paphies* species. For the large scale analysis the variables were seagrass leaf mass, seagrass root mass and tidal flat area, and the biomass or abundance of their potential prey. All data were examined for normality and homogeneity of variance using residual plots and exploratory data analysis and transformed where necessary using log transformations (Zar, 1999). Alpha (α) was set at 0.05.

Results

Shorebird abundance and distribution

A total of 4942 individuals of 19 species was observed during 116 surveys over the 18-month study period. The eight study species represented 77% of the total number of shorebirds (Table 1). Red-necked stints were the most numerous shorebird, followed in abundance by pied oystercatchers and double-banded plovers, while pied oystercatchers were the most frequently observed, recorded in 93% of the surveys. SP had the highest mean density of birds.ha^{-1} over the period (4.76), and all eight species were found at SP, while RP had the lowest mean density of birds (0.48) and number of species (2).

The water's edge at EI and SP had the greatest density of shorebirds overall, while the mid-intertidal stratum at SP and low intertidal stratum at EI had the greatest shorebird diversity (Fig. 2). The mid- and high intertidal strata at RP had the lowest number and diversity of birds respectively. Tidal level and site had a significant effect; however this pattern was not consistent, as there was a significant interaction between tidal level and site (Table 2). However a post-hoc Tukey test indicated that the water's edge zone generally had a significantly higher number of shorebirds.ha^{-1} (mean = 1.14) than did the low (0.37), mid- (0.23) and high (0.17) intertidal strata. The Tukey test also indicated that EI and SP (0.67 and 0.63, respectively) had a significantly greater number of shorebirds.ha^{-1} than did RP and WB (0.31 and 0.29, respectively). Site had a significant effect on shorebird diversity, although there was a significant interaction between tidal level and site (Table 2). The Tukey test indicated that SP generally had significantly greater mean diversity (1.83 species) than did EI (1.41), which had a significantly greater shorebird diversity than WB and RP (0.82 and 0.75, respectively).

Table 2. Results of three-way ANOVAs (fixed factor: tidal level, random factor: month and site) using shorebird abundance and diversity from the four different tidal levels at each of the four sites over the 18 months.

Factor	df	Abundance		Diversity	
		F	p	F	p
Tidal level	3	31.0	< 0.001	0.9	0.454
Site	3	5.2	0.019	3.7	0.051
Month	17	1.0	0.483	1.3	0.237
Tidal level*Site	9	3.9	< 0 001	7 9	< 0.001
Tidal level*Month	51	0.7	0.911	1.1	0.214
Site*Month	51	1 3	0.108	1.1	0.248
Tidal level*Site*Month	153	1.1	0.213	1.2	0 076
Error	176				

Table 3. Results of two-way ANOVAs (fixed factor: tidal level, random factor: month) using shorebird abundance from the four different tidal levels at each of the four sites over the 18 months.

Factor	df	East Inlet		Robbins Passage		Shipwreck Point		West Beach	
		F	p	F	p	F	p	F	p
Tidal level	3	54.6	< 0.001	40.5	< 0 001	18.9	< 0.001	28.8	< 0.001
Month	17	0.9	0.517	1.1	0.352	1.5	0.131	1.8	0.054
Tidal level*Month	51	1 0	0.441	1.3	0 144	1.1	0.352	0.7	0 868
Error	44								

Analysing each site separately for shorebird density and diversity, tidal level significantly affected shorebird density at each of the four sites (Table 3), with the Tukey test indicating that the water's edge had significantly more birds than the other strata at each site (Fig. 2). Tidal level also significantly influenced shorebird diversity at three of the four sites (EI, RP and SP: Table 4). The Tukey test showed that the tidal level with the greatest shorebird diversity varied among these three sites, with the low intertidal stratum at EI having significantly more shorebird species than the other strata; water's edge and low intertidal stratum having significantly more at RP, while at SP, the mid- and low intertidal strata had significantly more species than the other strata. Month had a significant effect on shorebird density and diversity at WB, although shorebird diversity showed a significant interaction between month and tidal level (Tables 3 and 4).

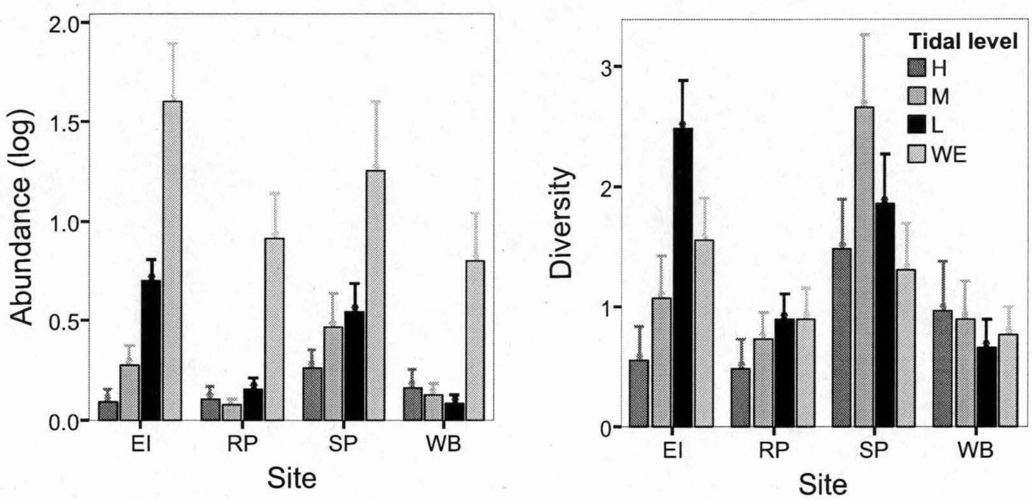

Figure 2. Mean number of shorebirds.ha^{-1} (± SE) and mean number of shorebird species per site (± SE) for each tidal stratum (H: High, M: Mid, L: Low, WE: Water's Edge) at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period.

RP was used only by the two oystercatcher species, while SP was used by all species (Fig. 3). Ruddy turnstones and Pacific golden plovers were found only at SP. Pied oystercatchers were the only species found at every site. Oystercatchers in particular appeared to favour the water's edge, as did red-necked stints, while the other species varied in their use of the tidal strata among sites.

As expected, the migratory species showed a distinct seasonality in their presence within the wetlands, with numbers of the Palaearctic species peaking in the summer, while numbers of double-banded plovers (from New Zealand) peaked in the winter months (Fig. 4). The residential species showed variation, but no annual pattern, in abundance in the Robbins Passage/Boullanger Bay wetlands during the study.

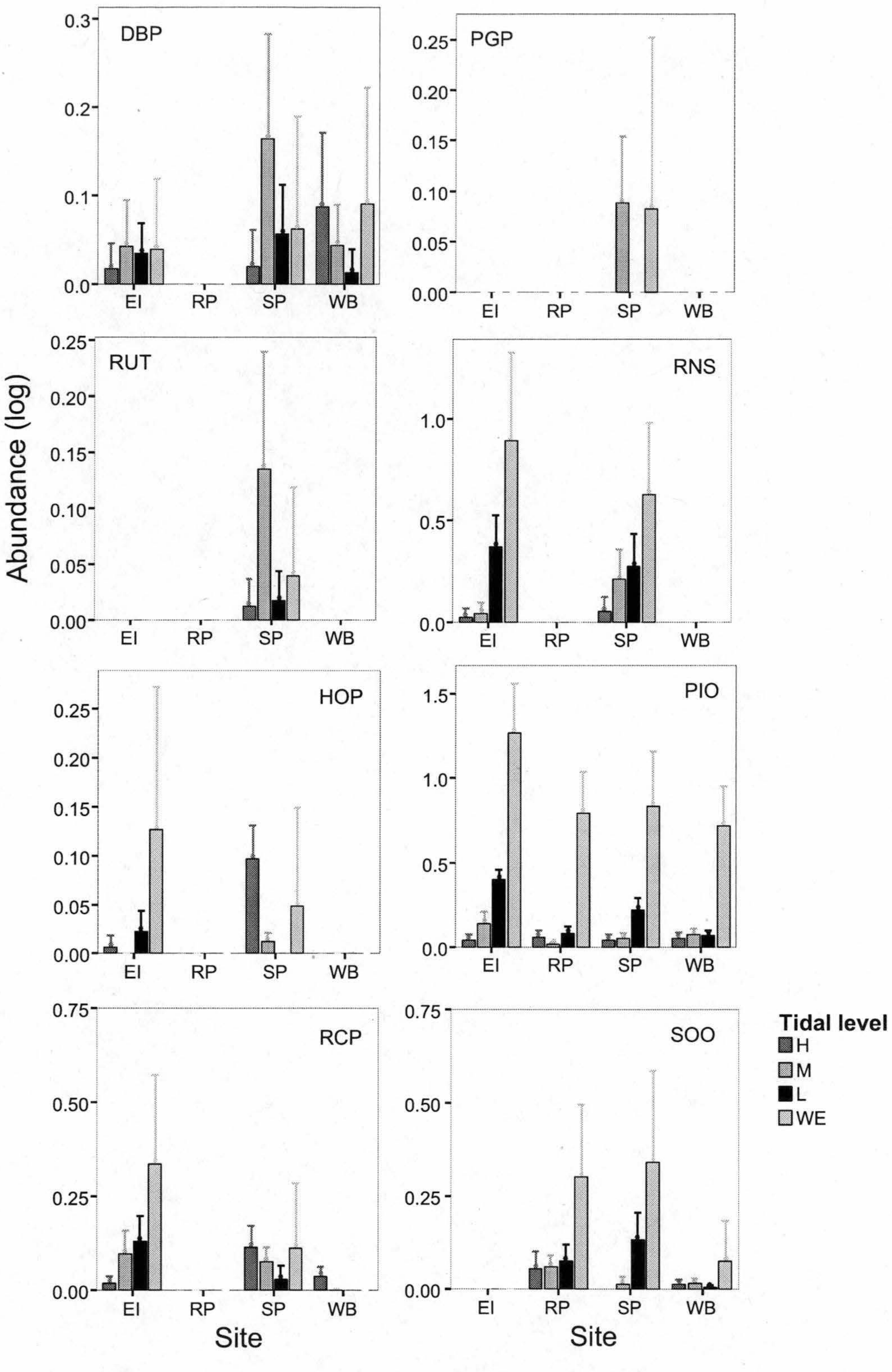

Figure 3. Mean number of shorebirds.ha^{-1} (± SE) for each species at each tidal stratum (H: High, M: Mid, L: Low, WE: Water's Edge) at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period. Species abbreviations: DBP: Double-banded plover, PGP: Pacific-golden plover, RNS: Red-necked stint, RUT: Ruddy turnstone, HOP: Hooded plover, PIO: Pied oystercatcher, RCP: Red-capped plover, SOO: Sooty oystercatcher.

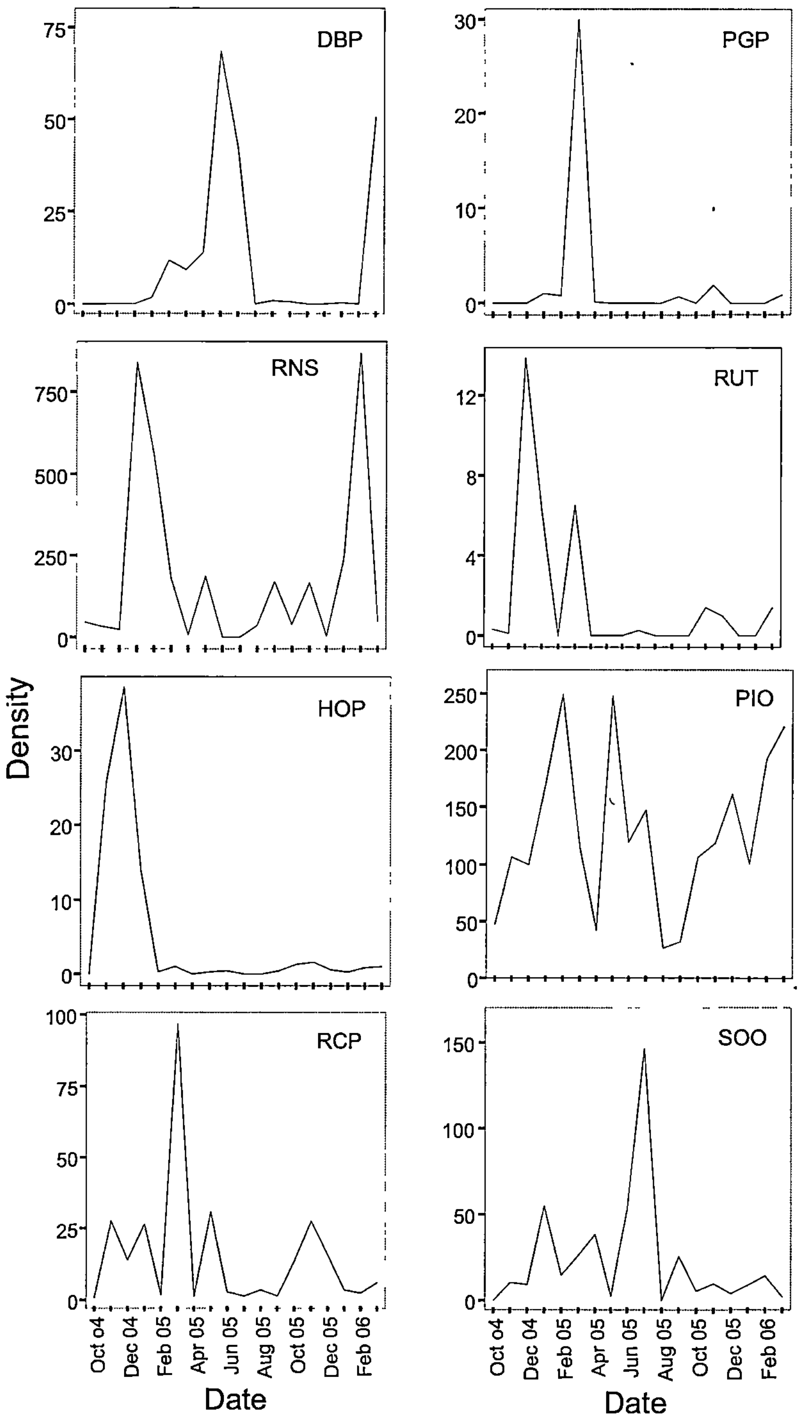

Figure 4. Total numbers per species of shorebirds.ha^{-1} at all four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania, during each month, over the whole sampling period. Species abbreviations: DBP: Double-banded plover, PGP: Pacific-golden plover, RNS: Red-necked stint, RUT: Ruddy turnstone, HOP: Hooded plover, PIO: Pied oystercatcher, RCP: Red-capped plover, SOO: Sooty oystercatcher.

Table 4. Results of two-way ANOVAs (fixed factor: tidal level, random factor: month) using shorebird diversity from the four different tidal levels at each of the four sites over the 18 months.

Factor	df	East Inlet		Robbins Passage		Shipwreck Point		West Beach	
		F	p	F	p	F	p	F	p
Tidal level	3	16.6	< 0 001	3.2	0.029	5.7	0.002	1.9	0.132
Month	17	1 3	0 182	0.9	0.492	0.9	0.554	1.8	0.046
Tidal level*Month	51	1.4	0 087	1.5	0.068	1.0	0.482	1.9	0 015
Error	44								

Community composition

Multivariate ordination (nMDS) illustrated that the shorebird community assemblages differed among sites, with EI and SP being distinctly separate from WB and RP (Fig. 5). A two-way ANOSIM verified that there was a statistically significant separation among sites, with some overlap present (predominately between EI and SP, and RP and WB: global $R = 0.579$, $p < 0.001$), and among tidal strata, predominately H and L, and M and L (global $R = 0.309$, $p < 0.001$). The separation was driven primarily by the presence of the Palaearctic species at EI and SP, and their absence at WB and RP.

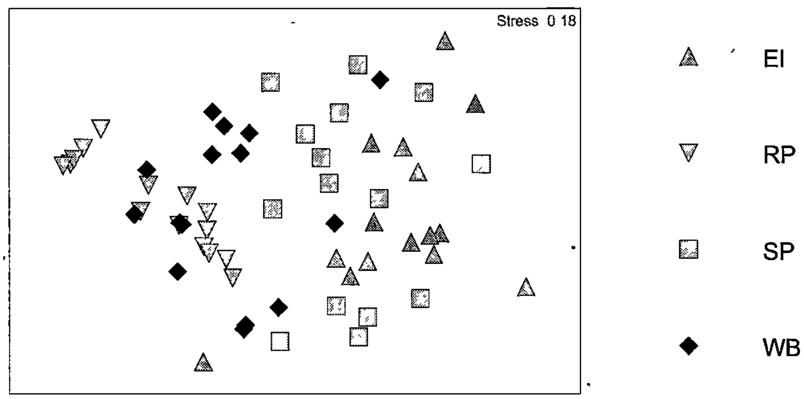

Figure 5. nMDS ordination plot showing shorebird assemblages at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach) over the whole sampling period and all tidal levels.

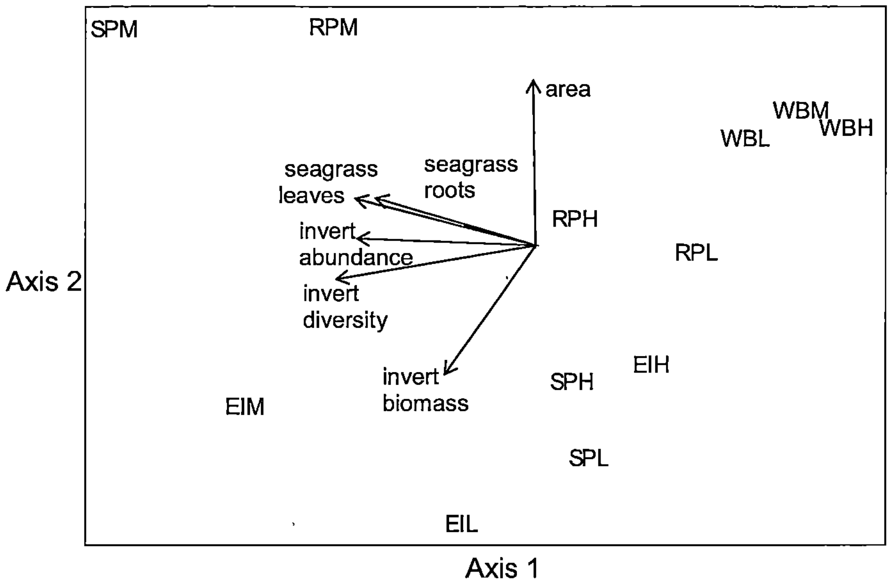

Figure 6. Results of principal components analysis for environmental and invertebrate variables, with bi-plot showing variables contributing to separation of points. Results shown for first two axes only. (EI: East Inlet, RP: Robbins Passage, SP: Shipwreck Point, WB: West Beach, H: High, M: Mid, L: Low)

Environmental variables

The derived values for the environmental variables are listed in Table 5. The first three axes of the PCA on habitat and invertebrate data explained 85.4% of the total variability (Table 6). PC1 axis, accounting for 43.4% of the variance, was best explained as an invertebrate-seagrass axis, representing decreasing values of invertebrate abundance, invertebrate diversity and seagrass biomass from left to right along the axis (Fig. 6). The second axis, accounting for 25% of total variance, had area of site positively loaded, with invertebrate biomass loading negatively. PC3 axis, accounting for 17% of the variance, was most strongly influenced by organic carbon and mean sediment size. Plots of factor scores for the first two axes showed separation among the sites, with EI and SP separated from RP and WB, where Palaearctic shorebirds were not found. The mid-intertidal sites of EI, RP and SP are conspicuous on the left side of Axis 1, where invertebrate abundance, diversity and seagrass biomass are increasing.

Table 5. Environmental and macroinvertebrate characteristics of the study sites. Means (± SD) are shown for data collected over five sampling periods (Spruzen *et al.*, 2007). (n = 50 except where stated otherwise)

Site	Tidal strata	Mean Sediment particle size (Φ) (n=7)	Organic carbon content (%) (n=1)	Mean vegetation cover (%) (n=20)	Mean mass of seagrass leaves (gDW)	Mean mass of seagrass roots (gDW)	Area (ha)	Invertebrate diversity (spp core^{-1})	Invertebrate abundance (ind.m^{-2})	Invertebrate biomass (gDW.m^{-2})
East Inlet	High	2.47 ± 0.35	1 18	0	0.01 ± 0 04	0 04 ± 0 13	4	5.5 ± 2.0	2572.5 ± 1420.9	21.69 ± 24.4
	Mid	2.43 ± 0.46	2.22	51.5 ± 43.08	0.41 ± 0.47	1.59 ± 1.93	4	8.0 ± 1.8	9695.0 ± 4177.8	73.23 ± 12.5
	Low	2.42 ± 0.44	3.14	2.5 ± 7.86	0.01 ± 0.07	0.02 ± 0.11	5	7.6 ± 1.8	6270 0 ± 3185.4	83.13 ± 43.5
Robbins Passage	High	2.50 ± 0.32	0.95	34.5 ± 41.78	0.16 ± 0.31	1.03 ± 0.90	3.2	4.2 ± 2.2	6702 5 ± 8983 1	9.61 ± 8.1
	Mid	2.46 ± 0.34	1.17	76.0 ± 23.26	0.50 ± 0.52	1.71 ± 0.99	8.8	6.3 ± 1.7	8637 5 ± 5458.8	15.19 ± 7.1
	Low	2.47 ± 0.32	0.94	27.5 ± 38.92	0.06 ± 0.10	0.27 ± 0.40	4.8	5 1 ± 1.6	1985 0 ± 1452.6	10.47 ± 3.8
Shipwreck Point	High	2.47 ± 0.36	2.70	19.0 ± 29.23	0.09 ± 0.16	1.06 ± 2.00	4	5.4 ± 1.8	4665.0 ± 4433.1	21.71 ± 4 5
	Mid	2.42 ± 0.46	1.51	84.5 ± 15 55	0.49 ± 0 59	4.95 ± 3.37	8	7 6 ± 1.7	14552 5 ± 15804.6	24.01 ± 11.7
	Low	2.43 ± 0.45	2.74	11.75 ±25.72	0.07 ± 0.14	0.69 ± 1.47	3	5.4 ± 2.2	4252.5 ± 3267.3	32 28 ± 3.8
West Beach	High	1.60 ± 1.20	2.90	63.5 ± 40.69	0.13 ± 0.18	0.81 ± 1.19	6	3 7 ± 1 4	1692.5 ± 1423.4	7.10 ± 1.6
	Mid	1.83 ± 0.78	2.31	13.0 ± 28.67	0	0	8	3.7 ± 1.8	5065 0 ± 2880 8	10.76 ± 5.5
	Low	2 08 ± 0 67	1 97	2.5 ± 9.10	0	0	8	2 9 ± 1.2	6230.0 ± 3590.9	16.37 ± 6.9

Table 6. Eigenvectors of habitat variables on first three axes of PCA

Variables	Principal component axis		
	1	2	3
Organic carbon		-0.318	-0.712
Sediment size	-0.338		0.507
Area	-0 440		
Seagrass leaves	-0.416	0.301	
Seagrass roots		0.558	-0.342
Invertebrate diversity	-0.463		
Invertebrate abundance	-0.439		
Invertebrate biomass	-0.314	-0.494	

for clarity, only loadings > 0.3 are shown

Shorebird densities in relation to environmental and invertebrate variables

Small spatial scale

The total combined feeding densities of all the shorebirds was positively correlated with invertebrate diversity and negatively correlated with seagrass leaf mass (Table 7). These two variables explained 29% of the variance in total shorebird density on the tidal flats. When the shorebirds were divided into resident, migrant and Palaearctic groups for analyses, invertebrate diversity was the sole predictor for migrant and Palaearctic shorebirds. The resident shorebird group had the greatest amount of variation explained by invertebrate diversity and seagrass leaf mass (39%).

Table 7. Multiple regression of shorebird groups on small scale habitat and invertebrate variables, with coefficients for successful predictors. * denotes significance at $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Response variable[a]	df	F	R^2	Invertebrate diversity	Seagrass leaf mass	Bivalve abundance
All shorebirds[b]	2	11.7***	0.29	0.096***	-0.385*	-
Resident shorebirds[b]	2	18.1***	0.39	0.066***	-0.529***	-
Migrant shorebirds[b]	1	7.2*	0.21	0.070*	-	-
Palearctic shorebirds[b]	1	13.9***	0.20	0 077***	-	-
Pecking shorebirds[b]	1	16.1***	0.22	0.118***	-	-
Probing shorebirds[c]	2	7.5***	0.21	-	-0.380**	0.097***

[a]refer to methods for shorebird groupings
[b]variables used: invertebrate diversity, seagrass leaves mass, area, sediment particle size.
[c]variables used: invertebrate abundance, invertebrate biomass, seagrass leaves mass, area, sediment particle size, bivalve abundance.

The shorebirds were also divided into groups based on their feeding guild, whether they predominately used pecking or probing feeding techniques. Pied and sooty oystercatchers were the larger-billed probing feeders of the eight study species, with the remainder predominately using a pecking and jabbing method (Dann, 1987). Pecking shorebirds had the same predictors as the migrant and Palaearctic groups, while the density of probing shorebirds was best explained by the abundance of bivalves and the absence of seagrass leaves. Bivalve abundance, made up predominately of *Katelysia* sp., was included in the analysis for the oystercatchers as bivalve molluscs are one of the main prey items of oystercatchers (Goss-Custard *et al.*, 1977c; Ribeiro *et al.*, 2004).

Of the eight shorebird species analysed individually, ruddy turnstones had the strongest result, with 30% of their feeding density explained by area of the tidal flat and the increasing biomass of bivalves and decreasing biomass of *Paphies* spp. (Table 8). Pied oystercatchers showed a weak relationship (21%) between the absence of seagrass leaves and bivalve biomass. Double-banded plover and red-necked stint showed no relationship with the variables, while the remaining species showed only very weak relationships (7% to 14%).

Table 8. Selected results of multiple regression of individual shorebird species on small scale habitat and invertebrate prey variables. * denotes significance at $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Shorebird species	Model predictors[b]	df	F	R^2
Ruddy turnstone	Area + Bivalve biomass + *Paphies* spp. biomass (-ve)	3	8.06***	0.30
Red-necked stint[a]	-	-	-	-
Pied oystercatcher	Seagrass leaves (-ve) + Bivalve biomass	2	7.43***	0.21
Sooty oystercatcher	*Paphies* spp. biomass (-ve)	1	9.34**	0.14
Pacific golden plover	Isopod biomass	1	5.18*	0.08
Red-capped plover	Area (-ve)	1	4.32*	0.07
Double-banded plover[a]	-	-	-	-
Hooded plover	Gastropod biomass	1	5.66*	0 09

[a]no result for these species.
[b]refer to methods for full list of variables entered into regression.

Large spatial scale

On larger spatial scales, invertebrate biomass and seagrass root mass explained between 58-73% of the variance in shorebird feeding density for five of the six shorebird groups, including all shorebirds combined (71%: Table 9). The feeding density of probing shorebirds was best explained by invertebrate biomass and the abundance of bivalves.

Table 9. Multiple regression of shorebird groups on large scale habitat and invertebrate variables, with coefficients for successful predictors. * denotes significance at $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Response variable[a]	df	F	R^2	Invertebrate biomass	Seagrass roots mass	Bivalve abundance
All shorebirds[b]	2	21.30	0.71	0.54***	0.10*	
Resident shorebirds[b]	2	23 59	0.73	0.26***	0.05*	
Migrant shorebirds[b]	2	13 12	0.61	0.54***	0.11*	
Palearctic shorebirds[b]	2	12 04	0.58	0 47***	0.12*	
Pecking shorebirds[b]	2	19.1***	0.69	0.65***	0.12*	
Probing shorebirds[c]	2	9.9**	0.54	0.09*		0.08**

[a]refer to methods for shorebird groupings
[b]variables used: invertebrate abundance, invertebrate biomass, seagrass leaves mass, seagrass roost mass.
[c]variables used: invertebrate abundance, invertebrate biomass, seagrass leaves mass, seagrass roost mass, bivalve abundance.

Table 10. Selected results of multiple regression of individual shorebird species on large scale habitat and invertebrate prey variables. * denotes significance at $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Shorebird species	Model predictors[b]	df	F	R^2
Ruddy turnstone	Seagrass roots	1	35.5***	0.66
Red-necked stint	Bivalve biomass	1	17.7**	0.49
Pied oystercatcher	*Paphies* spp. biomass + Bivalve biomass	2	39.1***	0.82
Sooty oystercatcher	*Paphies* spp biomass (-ve),+ Area	2	11.3**	0.57
Pacific golden plover	Seagrass roots	1	6.4*	0.26
Red-capped plover	Marine worms abundance (-ve) + Area (-ve)	2	7.7**	0.48
Double-banded plover[a]	-	-	-	-
Hooded plover	Seagrass roots	1	9.2**	0.34

[a]no result for this species.
[b]refer to methods for full list of variables entered into regression.

Pied oystercatchers had the strongest statistical result of the eight shorebird species, with 82% of their feeding density explained by bivalve and *Paphies* spp. biomass (Table 10). Sooty oystercatcher feeding density was related to area of the tidal flats and the absence of *Paphies* spp., while red-capped plovers were negatively related to marine worm abundance and area. Three species (hooded plover, Pacific golden plover and ruddy turnstone) had varying relationships with seagrass root mass and feeding density, while the feeding density of red-necked stints was best explained by bivalve biomass.

Better performing models were produced by the multiple regression process, but due to collinearity among variables, they were discarded (Appendix 1 & 2).

Discussion

Among-site distributions of shorebirds

The resident and migratory shorebirds were distributed non-randomly throughout the study sites within the Robbins Passage/Boullanger Bay wetlands. Shipwreck Point and East Inlet had the greatest densities and number of species of shorebirds. These two sites also had the greatest macro-invertebrate biomass and abundance of the four study sites (Table 5). However, in the multiple regression analyses, it was either invertebrate prey biomass or invertebrate diversity that accounted for varying degrees of variation in shorebird density on the feeding grounds, with the strongest relationship only accounting for 39% of this variation on a small spatial scale, but 82% on a larger spatial scale.

Invertebrate biomass or diversity explained shorebird feeding distribution to a greater extent than did invertebrate abundance. On a small spatial scale, five of the eight individual shorebird species showed a relationship with potential prey biomass, rather than abundance (Table 8), while on the larger spatial scale three of the eight shorebird species (Table 10) and all six shorebird groups (Table 9) had a moderate relationship with invertebrate biomass rather than abundance. This suggests that the biomass of the shorebirds' prey is more important for the selection of feeding areas by shorebirds than is prey abundance. Kalejta and Hockey (1994) found that the abundance of curlew sandpipers increased with greater invertebrate prey abundance, while grey plovers (*Pluvialis squatarola*) increased with greater invertebrate prey biomass. When feeding, shorebirds reach a maximum feeding rate, the rate at which they search and handle food, which may limit their overall intake or ingestion rate; prey regarded as unprofitable are ignored, as the handling time of some prey may lower the intake rate to below the average rate that could be maintained by feeding on other, more profitable prey (Zwarts & Blomert, 1992). However, if the shorebirds find an area with larger prey items and therefore greater biomass, the shorebirds may continue to increase their intake, meeting their energy requirements at a higher rate than if only smaller prey are available (Goss-Custard, 1977; van de Kam *et al.*, 2004). Goss-Custard (1970) hypothesised that redshanks (*Tringa totanus*) feeding efficiency on tidal flats was greatest in areas where prey biomass was greatest, as they obtained more mass of food per unit time in areas with greater prey biomass, even though feeding rate may have been slower, due to a longer handling time per unit prey. Although it must be noted that not all prey are harvestable by the shorebirds (Zwarts *et al.*, 1992; Zwarts & Wanink, 1993). Zwarts and Blomert (1992) found that knot (*Calidris canutus*) feeding on the bivalve *Macoma balthica*, ignored prey less than 9mm long as unprofitable, and could not swallow prey longer than 16mm, while prey below 2 to 3cm were inaccessible.

Another factor that has been found to influence foraging decisions in red knot, and may affect oystercatchers, is the digestive bottleneck; the rate of food processing is constrained by the rate of digestion by the gut (Zwarts & Blomert, 1992; van Gils *et al.*, 2005). Mollusc-eating shorebirds, who consume a certain amount of indigestible material, i.e. shell, with the digestible flesh, prefer prey types that contain high amounts of flesh relative to shell, as they yield high-energy assimilation rates (van Gils *et al.*, 2005). As shell mass increases more steeply with prey size than does flesh mass, this implies that the birds prefer smaller prey items; therefore the shorebirds select prey that are higher quality rather than more profitable (van Gils *et al.*, 2005). Eastern curlew (*Numenius madagascariensis*) were also found to limit themselves to higher quality prey in the pre-migratory period, in response to the decreasing size of their digestive system, including the gizzard, which reduced their ability to digest lower quality prey (Zharikov & Skilleter, 2004). Therefore prey biomass was still important, but instead of consuming a lower number of large items, the shorebirds consumed a greater number of small to mid sized items.

Invertebrate diversity had a weak, but significant, relationship with five of the six shorebird groups in the small spatial scale analyses. Diversity may have acted as a surrogate predictor for invertebrate abundance and biomass, which both had a strong positive correlation (> 0.6) with invertebrate diversity. Invertebrate diversity may also have been more important when considering the feeding distribution of a group of shorebird species, rather than just one, as a larger variety of prey items are consumed when considering multiple species.

The weak to moderate results from the regression models for individual shorebird study species on both spatial scales may be primarily due to the fact that the invertebrate prey for shorebirds in the Robbins Passage/Boullanger Bay wetlands have not been studied, and the choice of potential prey items for the analyses in this study was based on the existing literature. We also used broad prey groups (e.g. amphipods, isopods, etc.), rather than individual taxa. Yates *et al.* (1993) found that there is generally a strong association between shorebirds and their prey when the prey for that area is well known and consists of only one or two species. If the shorebird has multiple prey items, the proportion of each prey taken would need to be known in order to obtain a statistical relationship between the shorebird and prey densities (van de Kam *et al.*, 2004). However, if the shorebirds diet is relatively unknown or assumed, false relationships between the shorebirds density and supposed invertebrate prey density may occur. This relationship may also hide or replace the actual invertebrate prey in the regression (Yates *et al.*, 1993).

The strength of the relationship between shorebird and prey distribution is also dependent on the spatial scale of the study (Wilson, 1990; Colwell & Landrum, 1993). Studies of large estuaries or studies between estuaries, with spatial scales ranging from several to 50km, predominately show a strong positive correlation between shorebird and prey distribution (Goss-Custard *et al.*, 1977b; Goss-Custard *et al.*, 1977c; Placyk & Harrington, 2004). Smaller scale studies, with only one site or study sites spaced relatively closely together (< 1km), generally demonstrate weak, or absent, associations between shorebirds and their prey abundances (Dann, 1987; Wilson, 1990; Paton *et al.*, 2001). This may be due to decreased variation in physical variables, and therefore invertebrate distributions, within small scale studies, resulting in weaker relationships (Colwell & Landrum, 1993).

This study had a similar finding. The sites in the present study are a combination of large and small spatial scales. The four sites span a distance of 33km, with the three intertidal strata within each site spaced 10 to 100s of metres apart. The small spatial component of the study may well be obscuring larger spatial scale relationships. When the regression analysis was performed on a larger scale of the four sites, with tidal level removed, the strength of the relationships between shorebird feeding density and the environmental and invertebrate variables more than doubled for seven of the shorebird species (with no relationship for double-banded plover) and five of the six shorebird groups (resident shorebirds only increased from 39 to 73%).

The Robbins Passage/Boullanger Bay wetlands cover over 100ha, and we believe that there may be some substantial and potentially important feeding areas in the more remote western areas of the wetlands. These were not included in the current study due to logistical constraints that prevented surveys and sampling. However, inclusion of sites in that region may result in an even stronger relationship between shorebird and invertebrate density in the Robbins Passage/Boullanger Bay wetlands.

Seagrass leaf mass was a component in three of the six shorebird group regression models, also the pied oystercatcher regression, in the small spatial scale analysis and negatively influenced shorebird feeding density. Seagrass roots mass was a positive predictor for five of the six shorebird groups and three of the shorebird species at a large spatial scale. Due to a strong correlation between seagrass roots and leaves on the small spatial scale, seagrass roots mass was not entered into the small scale analyses. Seagrass leaves and roots may affect the birds' feeding method or it may be related to the shorebirds' prey distribution and abundance. For shorebirds using tactile foraging methods, seagrass may be a hindrance, interfering with bill sensitivity and the ability to detect prey (Moreira, 1999; Finn *et al.*, 2001). Short-billed species, such as plovers, feed mainly on prey located on or close to the surface relying on visual stimuli to locate their food (Dann, 1987). The seagrass may decrease the detectibility of prey, especially amphipods or worms. However, seagrass would also reduce the rate of desiccation of the sediment, encouraging the prey to remain close to the surface and available for predators, and making it easier for the shorebirds to jab and probe the sediment. Kalejta and Hockey (1994) found that grey plover preferred tidal flats with higher vegetation cover, and Zharikov and Skilleter (2002) found that bar-tailed godwits (*Limosa lapponica*) preferred seagrass covered flats, where prey choice may be wider, as increased seagrass mass led to increased invertebrate abundance and diversity (Kalejta & Hockey, 1994; Heck *et al.*, 1995; Edgar & Barrett, 2002; Spruzen *et al.*, 2007). In the present study, Pacific golden plovers, ruddy turnstones and double-banded plovers spent an equivalent amount of time foraging on flats with dense vegetation cover, as compared to bare flats, displaying opportunistic and flexible feeding styles. The preference for bare or covered flats may be related to what space is available and preferred prey and may also be a locality-specific foraging strategy. A simultaneous study (Spruzen *et al.*, 2007) investigating invertebrate composition and abundance at the study sites, found that the sites with the greatest seagrass mass had communities dominated by gastropods and annelids, while sites with less seagrass mass were dominated by the wedge shell, *Paphies elongata*. Bivalve filter feeders, such as *Paphies elongata* and *Katelysia* sp. would be able to feed more efficiently on bare tidal flats.

Sediment grain size explained little of the variation in shorebird feeding density. This was not unexpected, as the range of sediment grain size among the four sites was very low, ranging from medium (size) to fine (size) sand (Table 5). Previous studies, in which sediment type has ranged from coral to sand to mud, have found that sediment type and penetrability is an important determinant of shorebird feeding distribution (Congdon & Catterall, 1994; Finn *et al.*, 2007), with sediment particle size affecting invertebrate density and therefore shorebird density (Yates *et al.*, 1993).

Area of the tidal flats was a high-ranking factor in the PCA analysis and had a weak positive relationship with ruddy turnstone distribution on a small scale and a negative relationship with red-capped plover distribution on both small and large spatial scales. SP and EI, the sites with the greatest shorebird density, are the smaller of the four sites in area (Table 5). Previous studies (Evans & Dugan, 1984; Congdon & Catterall, 1994) have found that eastern curlews and Pacific golden plovers had a higher density on wider tidal flats. This may be attributed to an increased ability to see approaching predators or the availability of these flats for feeding, even on neap tides (Metcalfe, 1984; Congdon & Catterall, 1994). SP and EI also had the greatest invertebrate abundance and biomass, therefore tidal flat width may be irrelevant, with prey abundance and biomass the overriding factors.

Within-site distributions of shorebirds

The distribution of the shorebirds within each site of the Robbins Passage/Boullanger Bay wetlands was non-random, with the greatest densities of shorebirds present at the waters edge or in the low intertidal stratum, although this varied specifically. Red-necked stints and the two oystercatcher species showed a marked preference for the waters edge. Dann (1999b) also found that red-necked stints favoured areas of wet mud. These areas may be preferable because the remaining water increases the wetness of the substrate, which correlates with invertebrate activity and substrate penetrability (Dorsey, 1982; Evans & Dugan, 1984; Dann, 1999b). This would increase prey detectability for the shorebirds and make it easier to jab and probe the substrate in search of food (Kelsey & Hassall, 1989). Oystercatchers are focussed on rapid prey collection, as they store a proportion of their food in their glandular stomach for digestion at a later stage (van Gils *et al.*, 2005). Therefore they are not limited so much by digestion rates, but are more concerned with collecting prey quickly, making the ability to detect prey easily a priority for them. In the present study, the low intertidal strata had less seagrass present, which may be preferable for pied oystercatchers with their negative relationship with seagrass leaves in the regression analysis, and more beneficial to their bivalve prey, which are predominately filter feeders.

Conclusion

This study has shown that there are significant within-site differences in shorebird density and diversity on tidal flats within the Robbins Passage/Boullanger Bay wetlands. The shorebirds also appeared to select particular sites. This variation in shorebird density and diversity is partly explained by the invertebrate diversity and invertebrate prey biomass of the tidal flats, seagrass leaves and roots mass and tidal flat area. The spatial scale of the analysis greatly affected the strength and type of predictors influencing shorebird feeding density. While the relationships were moderately strong for the shorebird groups at larger spatial scales, they were still relatively weak for shorebird species (excepting pied oystercatcher) and very weak at small spatial scales. Further investigation is necessary to identify the remaining predictors of shorebird feeding density and reveal stronger relationships among shorebird densities and environmental and invertebrate variables. Future work may involve sampling at a larger number of sites scattered more widely throughout the wetlands, in particular sites not yet surveyed in the western reaches of the wetlands, and either measuring different variables at the sites or measuring the same ones differently. There also needs to be an investigation into the preferred prey items of the main shorebird species using the area, which would improve our understanding of the relationships among invertebrate prey and shorebird feeding density.

These results have important implications for future management of the Robbins Passage/Boullanger Bay wetlands, as not all areas of the wetlands are of equal importance to the shorebirds and we need to ensure that the important feeding areas on which the migratory and resident shorebirds rely are adequately protected.

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Appendix 1. Testing for collinearity of the independent variables for small scale analysis. Values indicate the Pearson's correlation coefficients for each variable. * denotes significance at $p < 0.05$, ** $p < 0.01$. Threshold for collinearity was $r > 0.6$.

	Invertebrate abundance	Invertebrate diversity	Invertebrate biomass	Seagrass cover[a]	Seagrass leaves mass	Seagrass roots mass	Sediment particle size[a]	Organic carbon content[a]
Invertebrate diversity	.621**							
Invertebrate biomass	.516**	.684**						
Seagrass cover[a]	.410	.267	-.266					
Seagrass leaf mass	.530**	548**	.202	.868**				
Seagrass root mass	.473**	.474**	.073	.826**	.730**			
Sediment particle size[a]	.018	.248	-.035	-.041	.261	.304		
Organic carbon content[a]	-.182	.004	.420	-.245	-.246	-.224	-.615*	
Area	.308*	-.116	-.166	.249	.294*	.276*	-.573**	-.064

[a]Spearman rank correlation was used for these variables.

Appendix 2. Testing for collinearity of the independent variables for large scale analysis. Values indicate the Pearson's correlation coefficients for each variable. * denotes significance at $p < 0.05$, ** $p < 0.01$. Threshold for collinearity was $r > 0.6$.

	Invertebrate abundance	Invertebrate diversity	Invertebrate biomass	Seagrass cover[a]	Seagrass leaves mass	Seagrass roots mass	Sediment particle size[a]	Organic carbon content[a]
Invertebrate diversity	.728**							
Invertebrate biomass	.440	790**						
Seagrass cover[a]	.016	-.264	-.605**					
Seagrass leaf mass	445*	.533*	.158	.574**				
Seagrass root mass	.452*	409	.105	.597**	.533*			
Sediment particle size[a]	.184	.380	-.037	.632**	.748**	.589**		
Organic carbon content[a]	-.411	-.884**	-.861**	.400	-.302	-.341	-.316	
Area	-.401	- 898**	-.799**	.400	.524*	-.414	-.316	.956**

[a]Spearman rank correlation was used for these variables.

Chapter 4

Influence of tidal level on coastal habitat use by shorebirds within the Robbins Passage/Boullanger Bay wetlands, Northwest Tasmania.

Abstract

Shorebirds generally forage on intertidal flats, preying on intertidal invertebrates that live in or on the sediment and as such, their feeding time is ruled by the tides. The aims of this study were to determine the use of four sites in the Robbins Passage/Boullanger Bay wetlands by shorebirds over an extended period of the tidal cycle and to ascertain whether low tide counts are accurate measures of shorebird use of a potential feeding site and among tidal strata within a site. Shorebird density did not differ significantly during the ebbing tidal cycle, while shorebird abundance was only significantly different at East Inlet and Robbins Passage, with the greatest numbers of shorebirds observed two hours before low tide at East Inlet, and four and zero hours before low tide at Robbins Passage. The feeding distribution of pied oystercatchers and red-necked stints over the tidal flat during the ebbing tidal cycle was non-random. Pied oystercatchers were observed in greater numbers along the water's edge, and the low intertidal stratum at East Inlet, while red-necked stints also fed along the water's edge in greater numbers than expected, but at East Inlet they also preferred the low intertidal stratum, while at Shipwreck Point they preferred the mid-intertidal stratum. These results suggest that mid- and low tidal counts should be conducted if all important shorebird feeding sites within a wetland are to be identified.

Introduction

Many species of shorebirds breed in the Northern Hemisphere, before migrating to overwintering sites in the Southern Hemisphere, where they spend the austral summer months fattening up for their moult and then preparing for their flight back to their breeding grounds (Lane, 1987). One of the primary criteria on which shorebirds select these sites, typically coastal wetlands and estuaries, is therefore a predictably abundant and accessible supply of prey (van de Kam *et al.*, 2004). At these overwintering sites, the shorebirds' movements are ruled by the tides. As their main feeding areas are tidal flats, when these flats are covered at high tide the birds move into high-tide roosts, where they rest and preen (van de Kam *et al.*, 2004). As the tides recede, the shorebirds move out onto the tidal flats and resume their foraging.

Many studies have investigated shorebird feeding distributions and habitat use in coastal wetlands (e.g. Goss-Custard *et al.*, 1977b; Dann, 1991; Piersma *et al.*, 1993b). The majority of these studies used counts of shorebirds at low tide (Finn *et al.*, 2001): however, determining shorebird abundance in such surveys, could result in inaccurate results if the entire wetland is not counted (Burton *et al.*, 2004; Dias *et al.*, 2006b). More commonly, investigators study the use that shorebirds make of habitats for feeding. Once again, the use of low tide counts only at selected sites within the wetlands, may underestimate shorebird use of a site, as birds may visit a number of feeding sites over the tidal cycle. This may thereby result in an underestimate of the importance of potential feeding areas (Dias *et al.*, 2006b).

A number of studies have investigated shorebird movements among habitats during the tidal cycle, focussing on their use of a variety of habitats, such as pasture, salt marsh, beach and tidal flats over the full tidal cycle (Burger *et al.*, 1977; Long & Ralph, 2001; McConkey & Bell, 2005). Fewer studies have looked specifically at how shorebird habitat use varies on tidal flats over the tidal cycle (Burger *et al.*, 1997; Fasola & Biddau, 1997; Burton *et al.*, 2004; Dias *et al.*, 2006b).

The Robbins Passage/Boullanger Bay wetlands in northwest Tasmania are the most important shorebird site in Tasmania (Woehler, 2007) and qualify for Ramsar listing, meeting seven of the nine criteria (Dunn, 2000; Gardner & Connolly, 2007). Previous studies conducted at Robbins Passage/Boullanger Bay wetlands have investigated shorebird habitat use at low tide only (Spruzen *et al.*, 2008). The aims of this study were to determine the use of four sites by shorebirds over an extended period of the tidal cycle and to ascertain whether low tide counts are accurate measures of shorebird use for a potential feeding site. Two specific questions were addressed:

1. Is shorebird feeding abundance or density greatest at low tide? And if not;
2. What are the temporal and spatial feeding distributions of two shorebird species at each site over the tidal flat during the ebbing tide?

Method

Study area

Located in the far northwest of Tasmania (40° 40'S, 144° 50'E), the Robbins Passage/Boullanger Bay wetlands are a coastal intertidal wetland with an area exceeding 100km^2 (Dunn, 2000). The area comprises two large shallow tidal basins, Boullanger Bay and Big Bay, and a number of smaller tidal areas, with an average tidal range of 3.5m (DPIWE, 1999a). The wetlands are an extensive area of tidal channels and intertidal sand flats that comprise approximately 65% of the total site area (Fig. 1) (Dunn, 2000). The wetlands also have one of the largest seagrass areas in temperate Australia, covering an area of approximately 8000ha, dominated by *Posidonia australis*, with substantial areas of *Heterozostera tasmanica* and *Amphibolis antarctica* (Rees, 1993; DPIWE, 1999a). In addition to being the most important shorebird site in Tasmania, the Robbins Passage/Boullanger Bay wetlands are also a site of international significance for five migratory shorebird species: curlew sandpipers, double-banded plovers, red-necked stints, red knot and ruddy turnstones, and of national importance for two resident species: pied and sooty oystercatchers (Watts, 1999; Woehler & Park, 2006; Woehler, 2007).

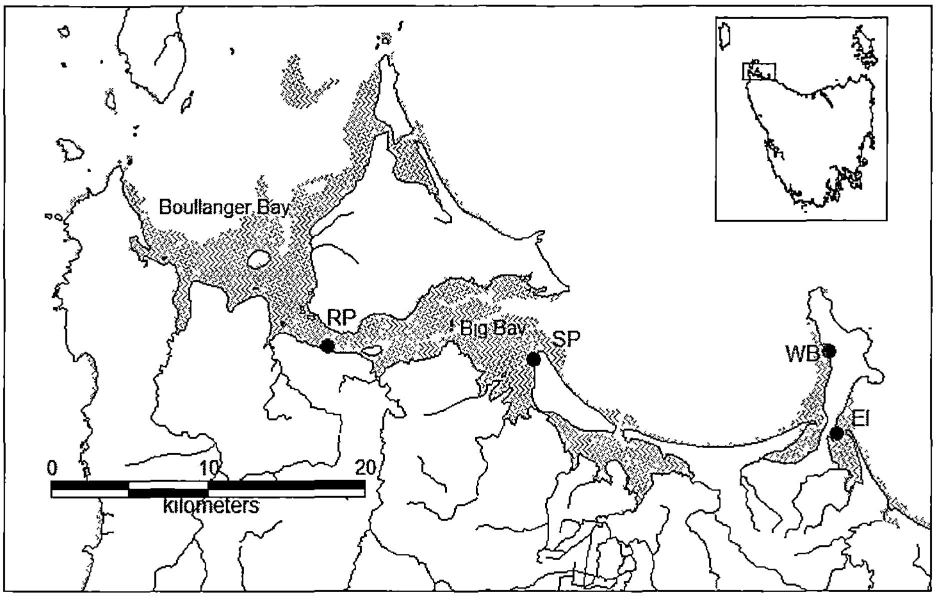

Figure 1. Map of northwest Tasmania showing the location of the four shorebird feeding sites surveyed in this study. Stippled areas represent tidal flats (EI = East Inlet, RP = Robbins Passage, SP = Shipwreck Point, WB = West Beach).

Survey methods

The distribution of feeding shorebirds over the tidal cycle was investigated at four intertidal flats spread across the Robbins Passage/Boullanger Bay wetlands, East Inlet, Robbins Passage, Shipwreck Point and West Beach, which together extend approximately 33km along the coast (Fig. 1). The choice of sites was determined by a concurrent study examining shorebird habitat use and environmental variables (Spruzen *et al.*, 2008), although it was also influenced by accessibility, logistics and safety considerations, since much of the area is very remote. Shorebird surveys were conducted during January and February 2006, and each site was surveyed three times. The four sites were visited on consecutive days, the order of visits being randomly determined. Shorebird counts were conducted during the ebbing tide only, as it was logistically difficult to access one of the sites for both the ebbing and rising tide. All surveys were conducted during daylight, although some shorebird foraging occurs at night (Dodd & Colwell, 1998).

Each site consisted of a 400m long section of sand/mud flat, and due to the varying slopes at each of the sites, the intertidal width of the sites at low tide varied between 400m and 600m, while the area of the sites ranged from 13-22ha. Shorebird surveys of each of the feeding sites began one hour after the predicted high tide, and continued until one hour after predicted low tide. Each site was scan-sampled (Altmann, 1974) at regular intervals (15 minutes) by an observer positioned along the shoreline of the site. The area was scanned with a pair of *Nikon* 8x42 binoculars and a 32x *Kowa* (TSN- 821) spotting scope. The observer walked along the high water mark to minimise disturbance to the feeding shorebirds.

During the surveys each shorebird was counted, identified to species and its location on the tidal flats recorded as high, mid- or low intertidal flat, or water's edge (the narrow 1-2m strip between the dry mudflat and open water, covered by a thin surface layer of water), and the position of the water line and percentage of tidal flat exposed was also recorded. A *Leica* Rangemaster was used to enable the observer to calculate the amount of flats exposed at each count.

A one-way repeated measures analysis of variance (ANOVA) was used to compare total shorebird abundance (mean number of shorebirds) and shorebird density (mean number of shorebirds.ha^{-1}) at each site during the ebbing tide. Due to a departure from sphericity in the repeated measures factor, degrees of freedom were adjusted using Greenhouse-Geisser estimates of sphericity. The densities of pied oystercatchers and red-necked stints (the most abundant resident and migratory species respectively) were graphed to see how these species used the sites during the ebbing tide. All data were examined for normality and homogeneity of variance using residual plots and Shapiro-Wilk test, and variance was reduced by a logarithmic transformation of the data (Zar, 1999).

Results

During the 12 survey days, a total of 14 shorebird species was observed, with Shipwreck Point being the only site where all 14 species occurred (Table 1). Shipwreck Point also had the highest single count of shorebirds (n=1819). Red-necked stints were the most abundant shorebird at Shipwreck Point and East Inlet, while masked lapwings were the most abundant at Robbins Passage and West Beach (Table 1). Figure 2 shows the mean shorebird abundance on the tidal flats at each site, during the ebbing tide. Although the variances are large, a general pattern can be observed at each site. Shorebird abundances peak at Shipwreck Point approximately four hours before low tide, while East Inlet and West Beach show peak numbers two hours and one hour before low tide, respectively. Robbins Passage is rather irregular, with maximum numbers occurring four hours before low tide, and then again at low tide. The difference in shorebird abundance during the tidal period was statistically significant at East Inlet and Robbins Passage (Table 2).

Table 1: Species observed during surveys and their mean abundance (± SD) at each site over the three survey periods. Species listed in taxonomic order.

Common name	Species name	East Inlet	Robbins Passage	Shipwreck Point	West Beach
White-faced heron	*Egretta novaehollandiae*	1.0 ± 0.2	3.5 ± 1.8	1.4 ± 0.5	1.0 ± 0
Ruddy turnstone*	*Arenaria interpres*	-	-	12.6 ± 13.1	-
Red knot*	*Calidris canutus*	-	-	3.0	-
Red-necked stint*	*Calidris ruficollis*	49.9 ± 57.6	-	277.4 ±452.0	-
Curlew sandpiper*	*Calidris ferruginea*	-	-	29.1 ± 12.8	-
Pied oystercatcher	*Haematopus longirostris*	13.3 ± 6.7	2.4 ± 1.3	2.9 ± 1.4	4.9 ± 3.2
Sooty oystercatcher	*Haematopus fuliginosus*	-	3.4 ± 1.8	2.9 ± 2.5	2.0
Pacific golden plover*	*Pluvialis fulva*	-	-	11.5 ± 17.1	-
Red-capped plover	*Charadrius ruficapillus*	2.7 ± 1.9	-	9.3 ± 13.5	2.5 ± 0.8
Double-banded plover*	*Charadrius bicinctus*	-	-	1.7 ± 0.4	-
Hooded plover	*Thinornis rubricollis*	1.4 ± 0.8	-	1.7 ± 0.9	-
Masked lapwing	*Vanellus miles*	1.9 ± 0.6	4.7 ± 5.4	1.2 ± 0.5	7.9 ± 9.3
Pacific gull	*Larus pacificus*	1.7 ± 0.7	1.0 ± 0	1.4 ± 0.6	1.4 ± 0.5
Silver gull	*Larus novaehollandiae*	3.2 ± 2.1	1.3 ± 0.6	2.0 ± 1.4	2.9 ± 1.3

*migratory species

This pattern of peak shorebird abundances is also clear in Figure 3, where the shorebird counts are expressed as a percentage of each site-specific maxima, during the ebbing tide. Shipwreck Point and Robbins Passage both have their maxima four hours before low tide, but instead of numbers staying relatively constant, as they did at Robbins Passage, the numbers of shorebirds at Shipwreck Point decreased dramatically after this peak, to less than 10% of the maximum. East Inlet also shows a sharp decrease after shorebird numbers there reached maximum abundance, but it is not as dramatic, and stayed above 25% of the maximum count. When the cumulative numbers of shorebirds (as percentages) are graphed against the percentage of tidal flats exposed at each count,

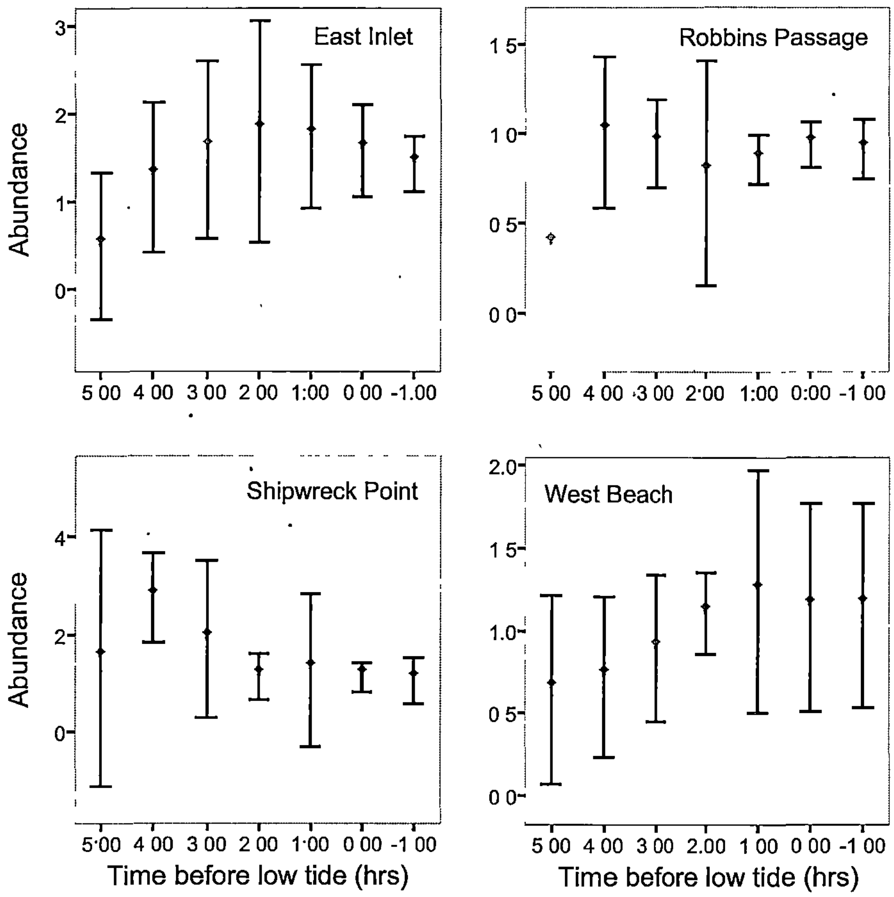

Figure 2: Mean total numbers of shorebirds (± SD) (n = 3 surveys) on tidal flats during ebbing tidal cycle, at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania. (0:00hrs = Low tide, -1.00hrs = 1 hour after Low tide). Note log axis.

Shipwreck Point shows a convex curve; reaching its maximum number of shorebirds (greater than 75% of cumulative abundance) before half of the tidal flats are exposed. The remaining three sites show a concave relationship, with fewer than 50% of shorebirds having visited the tidal flats before they are 50% exposed (Fig. 4).

Table 2. Results of the one-way repeated measures ANOVA, evaluating the abundances of shorebirds in relation to tide time (repeated measures factor). Data were log-transformed. GGE = Greenhouse-Geisser Epsilon.

Site	GGE	df	df error	MS	F	p
East Inlet	0 324	1.94	3.89	1.47	15.42	**0.014**
Robbins Passage	0 218	1.31	2.61	1.24	11.73	**0.050**
Shipwreck Pt	0.174	1.04	2.08	6.13	3.44	0.201
West Beach	0.234	1.40	2.81	0.54	3.39	0.174

Table 3. Results of the one-way repeated measures ANOVA, evaluating the densities of shorebirds in relation to tide time (repeated measures factor). Data were log-transformed. GGE = Greenhouse-Geisser Epsilon.

Site	GGE	df	df error	MS	F	p
East Inlet	0.324	1.94	3 89	0.20	2.60	0 192
Robbins Passage	0.173	1.03	2.07	1.26	3.68	0.191
Shipwreck Pt	0.169	1.01	2.03	7 62	5 35	0 145
West Beach	0.285	1.71	3.42	0 12	3 22	0.163

When shorebird density, rather than raw abundance, is graphed against the ebbing tide height, the findings are quite different (Fig. 5). East Inlet has a relatively constant shorebird density during the ebbing tide, with a slight decrease around low tide. The remaining three sites (Robbins Passage, Shipwreck Point, and West Beach) all have similar patterns, with a suggestion of a peak in shorebird density four to five hours before low tide and then a lower but relatively constant density for the remainder of the ebbing tide. However, the repeated measures ANOVA showed that these variations were not statistically significant (Table 3).

The density of pied oystercatchers and red-necked stints was graphed against the ebbing tide height (Fig. 6). At Shipwreck Point, red-necked stints showed a peak density four hours before low tide, with more than 80 birds.ha^{-1}, but this decreased dramatically three and two hours before low tide to 12 and 0.4 birds.ha^{-1}, respectively. Pied oystercatchers were present in relatively low, constant numbers, during the ebbing tide. East Inlet also had a sharp peak in red-necked stint abundance, although it occurred two hours before low tide, and then decreased dramatically, while pied oystercatchers had over 4 birds.ha^{-1} four hours before low tide, which was approximately halved an hour later and remained relatively constant for the remainder of the ebbing tide. Robbins Passage and West Beach were similar, with no red-necked stints present at any time, and pied oystercatcher density highest four to five hours before low tide, before decreasing to lower values for the remainder of the ebbing tide, although pied oystercatcher density was very low throughout the ebbing tide at both sites (mean = 1.1 and 0.6 birds.ha^{-1}, respectively). Despite these apparent patterns, a repeated measures ANOVA showed that none of these variations were statistically significant.

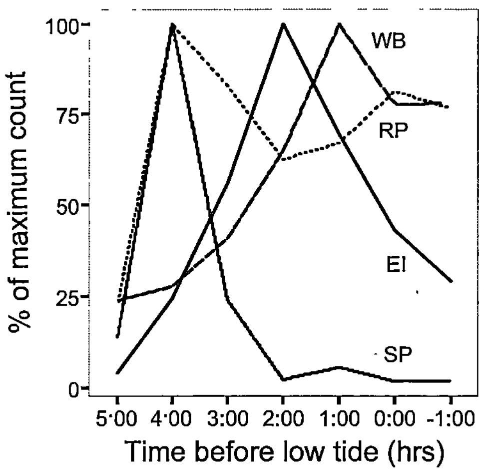

Figure 3: Percentages of maximum average feeding shorebird count at each site each hour during the ebbing tide. (0:00hrs = Low tide, -1.00hrs = 1 hour after Low tide).

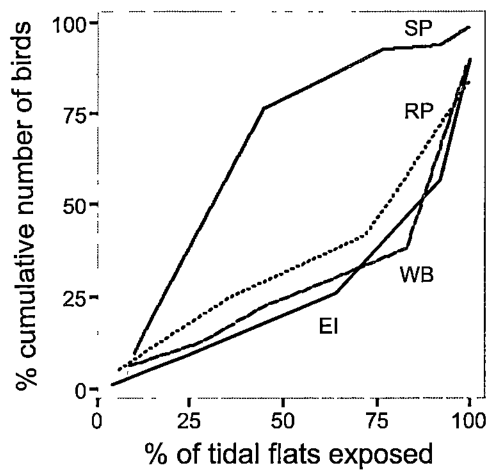

Figure 4: Percentages of cumulative number of shorebirds at each site as the tidal flats are exposed.

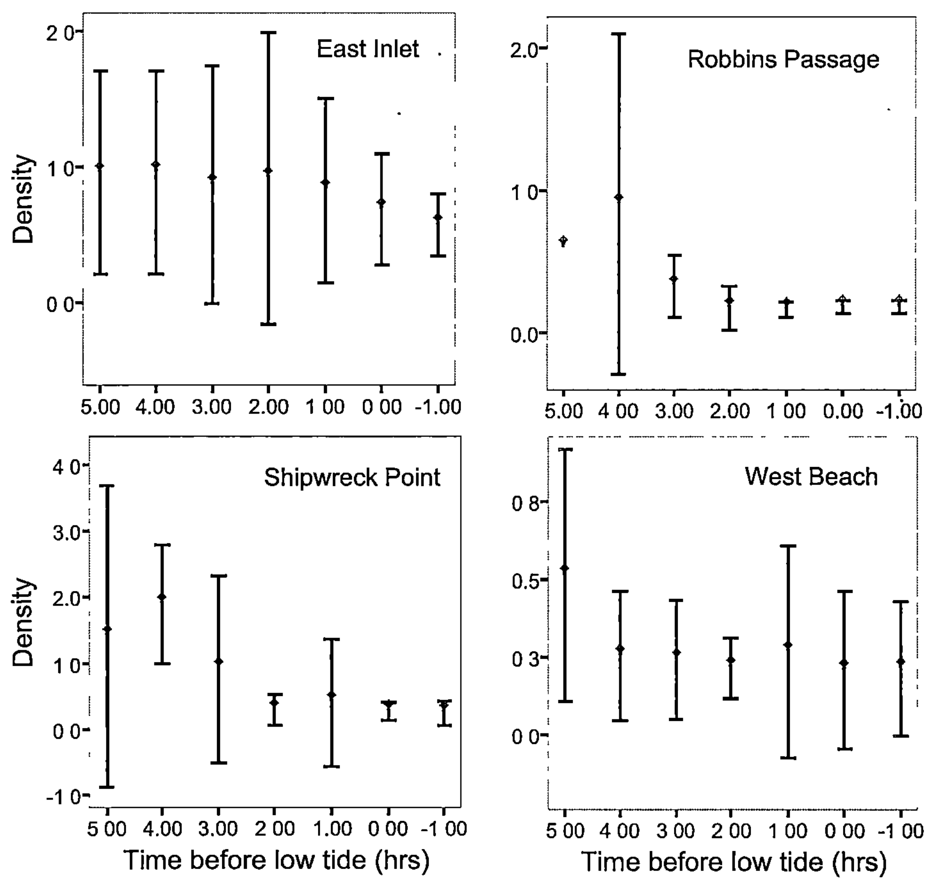

Figure 5: Mean numbers of shorebirds.ha^{-1}($\pm$ SD) (n = 3 surveys) on tidal flats during ebbing tidal cycle, at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania. (0:00hrs = Low tide, -1.00hrs = 1 hour after Low tide). Note log axis.

The distribution of pied oystercatchers and red-necked stints on the tidal flats during the ebbing tide was non-random, apart from for a few exceptions, and showed that both species favoured the water's edge (Fig. 7). Pied oystercatchers had particularly high densities feeding along the water's edge at all sites, and they moved onto the low intertidal strata as it became available. Although they also showed a preference for the water's edge, red-necked stints also had higher densities in the mid-intertidal strata at Shipwreck Point, and continued to use this area even when the low intertidal stratum was available. At East Inlet, red-necked stints had their highest densities at the water's edge and the low intertidal stratum, moving onto that zone as soon as it became available.

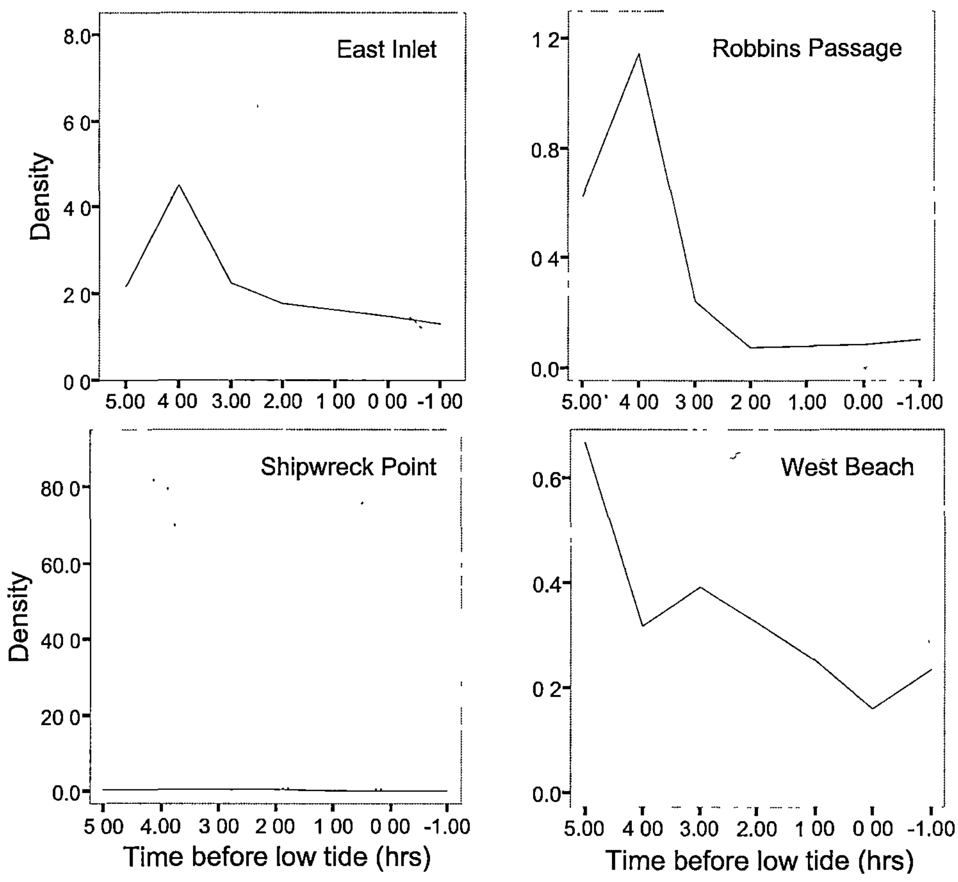

Figure 6: Mean numbers of pied oystercatchers and red-necked stints (shorebirds.ha^{-1})(n = 3 surveys) on tidal flats during ebbing tidal cycle, at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania. (pied oystercatchers = solid line, red-necked stints = stippled line) (0:00hrs = Low tide, -1.00hrs = 1 hour after Low tide).

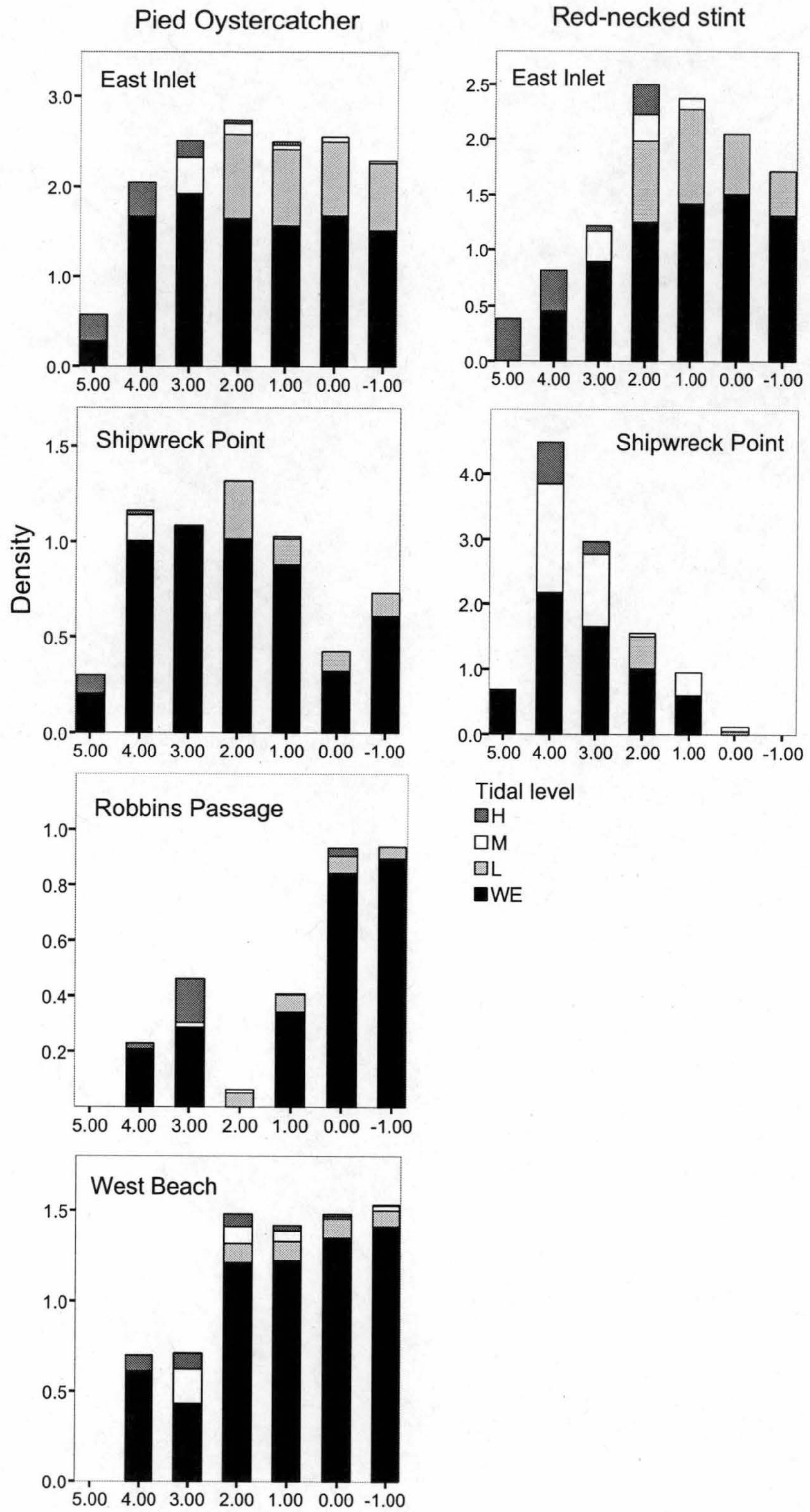

Figure 7: Mean numbers of shorebirds.ha^{-1} ($n = 3$ surveys) on tidal flats during ebbing tidal cycle, at four sites in the Robbins Passage/Boullanger Bay wetlands, Tasmania. (H = High, M = Mid, L = Low, WE = Water's edge) (0:00hrs = Low tide, -1.00hrs = 1 hour after Low tide). Note log axis.

Discussion

In this study, shorebird densities did not differ significantly over the ebbing tidal cycle, but shorebird abundances differed significantly at two of the four sites. However, care should be taken when drawing conclusions about shorebird feeding areas if the data analysed are only from low tide surveys, as some earlier studies have found significant differences between low tide counts and other counts during the tidal period (Burton *et al.*, 2004; Dias *et al.*, 2006b). Burton *et al* (2004) compared shorebird abundances during the tidal cycle and found significant variation in counts of shorebirds, although it varied among sites and species. Dias *et al* (2006b) focussed on shorebird densities rather than abundance, (as did this study), and compared low-tide densities with shorebird densities during the whole ebbing or rising tide (full cycle counts). They found that low tide counts were significantly lower than full cycle counts, but once again this varied among the species observed. The results from the current study are somewhat inconclusive, due to the high variances, and a greater number of surveys would be required to obtain a clearer picture. Despite the lack of significance, we will discuss the apparent trends in the data.

The trends in the data collected suggested that the time of peak shorebird feeding densities varied at each site during the ebbing tide (Fig. 5). While Shipwreck Point, Robbins Passage and West Beach showed peak densities 4-5 hours before low tide, East Inlet had its greatest shorebird density two hours before low tide, when approximately 90% of the tidal flats were exposed. Red-necked stint at East Inlet also had their greatest density at this time. A number of studies have found peak shorebird feeding density just before, during and after low tide (Connors *et al.*, 1981; Reinert & Mello, 1995). This is not unexpected, as it is reasonable to expect that all the shorebirds will be feeding by this stage of the tidal cycle and would spend low tide at their feeding areas, taking advantage of the exposed flats.

Shipwreck Point had the greatest shorebird density (mean = 95.9 birds.ha^{-1}) which occurred four hours before low tide. At this stage in the tidal cycle, the high intertidal stratum was fully exposed and the mid-intertidal stratum was approximately 40% exposed. This peak in shorebird density can be attributed primarily to the presence of red-necked stints (mean = 87.6 birds.ha^{-1} four hours before low tide), when the stints were feeding mainly on the water's edge and the mid-intertidal area (Fig. 7). Within 500m of this tidal feeding area there is a traditional roost that is frequently used by approximately 2000 red-necked stints during the summer months (unpubl. data, see Ch 5). As soon as the mid-intertidal stratum became exposed, the stints from the nearby roost arrived to feed. However, the majority of the stints did not stay for long, and by the time the low intertidal stratum started to become exposed (2-3 hours before low tide) there was less than one red-necked stint.ha^{-1}. It is likely that the stints moved to another, more profitable (energy-wise) and as yet unidentified, feeding area which becomes exposed later in the tidal cycle, either due to the fact that it is situated lower on the tidal flat or there is a spatio-temporal lag in the tidal cycle within the wetlands, so that different areas of the wetlands are exposed sequentially. Robbins Passage/Boullanger Bay wetlands extend 30km along the coastline, and low-tide at the eastern end occurs approximately 75mins earlier than at the western end. Red-necked stint may therefore be able to move from one feeding site to another, exploiting their preferred tidal stratum, as it becomes exposed at each site. Danufsky and Colwell (2003) found a similar situation with long-billed curlews (*Numenius americanus*), as they moved from their roost to nearby tidal flats and then dispersed to territories as the tide receded farther, exposing more foraging area. The movement of stints among tidal flat habitats that may be exposed at different times, allows the birds to utilise a number of habitats within the tidal cycle, thereby extending their foraging time and potentially increasing their energy intake (Burger *et al.*, 1977; Connors *et al.*, 1981).

The spatial distributions of pied oystercatchers and red-necked stints are indicative of their preferences for certain areas of the tidal flats within the wetlands (Fig. 7). Pied oystercatcher densities were greatest along the water's edge, with the low intertidal stratum also preferred. However it can be seen that the oystercatchers used all areas of the tidal flat, following the water's edge as it moved through the high, mid- and low intertidal strata. This suggests a preference for wet, recently exposed sand that has not yet dried out. Wet substrates are easier to penetrate by probing and jabbing and positively affects detectability and accessibility of prey (Evans, 1979; Colwell & Landrum, 1993). Studies have found that burrowing prey are usually closer to the surface, while surface prey are usually more active, in a wetter substrate (Evans, 1979). This allows the shorebirds to be able to detect their prey more easily and to be able to capture prey before it is out of reach beneath the substrate. Pied oystercatchers feed mainly on burrowing bivalves and worms, which are more visible in a wet substrate or substrate with a thin film of water, such as at the water's edge (Pringle, 1987). Siegel-Causey (1991) found that the foraging zones of American (*Haematopus palliatus*) and Magellanic (*H. leucopodus*) oystercatchers in Patagonia were also focussed along the water's edge, presumably where the prey's increased surface activity enabled the oystercatchers to detect them.

The density of red-necked stints followed a similar pattern at East Inlet, while at Shipwreck Point they favoured the mid-intertidal stratum. At Shipwreck Point, the mid-intertidal stratum has a moderate covering of seagrass which ensures that it retains a film of water at low tide. This would enable the stints to detect surface movements by amphipods, small gastropods and worms, their preferred prey (Pringle, 1987; Dann, 1999b). An earlier study in Victoria by Dann (1999b) found that red-necked stints preferred the wet mud zone and predominately used a pecking motion to take prey from the surface. Spruzen *et al* (2007) investigated macroinvertebrate abundance and biomass within the Robbins Passage/Boullanger Bay wetlands and found that the presence of seagrass lead to increased invertebrate diversity and abundance, and the mid-intertidal stratum generally had the greatest invertebrate density and diversity, while the low intertidal stratum had the greatest biomass. Of the four sites, the mid-intertidal stratum at Shipwreck Point had the greatest invertebrate abundance (Spruzen *et al.*, 2007).

Shorebird feeding abundance and density differed during the ebbing tide, but apart from shorebird abundance at East Inlet and Robbins Passage, these differences were not statistically significantly. While shorebird abundances appear to show variations during tidal cycles, this is not an issue if the whole system is being counted, as the birds will be included wherever they are. However, with shorebird density, if a tidal flat is only counted at a certain time every time, the researchers may underestimate the total shorebird use of that particular tidal flat or sections of that tidal flat (Dias *et al.*, 2006b). This could result in important feeding areas being overlooked for appropriate management and conservation strategies. The variations among sites and species make it difficult to determine an optimum counting period. Dias *et al* (2006b) recommend a mid- and low intertidal count, while Burton *et al* (2004) concluded that low tide counts are the best option for many species of shorebirds. Low-tide counts are adequate if the purpose of the study is to compare the relative use of sites by feeding shorebirds. However, if the aim of a study is to identify all of the important shorebird feeding sites within a system, then at least mid- and low intertidal counts should be conducted, as recommended by Dias *et al* (2006b).

Future studies in the Robbins Passage/Boullanger Bay wetlands should first repeat this study on a larger scale and with more surveys, incorporating Power analyses, to verify these results, as the variances in the data are large. Future investigation could consider the marking of shorebirds to ascertain whether individuals stay at a particular site and follow the falling tide down the flats, or whether there is a flux of feeding birds at a site, and then they move on and are replaced by other birds. Simultaneous surveys at other areas within the wetlands could identify possible alternative feeding areas that the shorebirds may be moving to, in particular, the red-necked stints. Future studies should also attempt to determine shorebird diet in the Robbins Passage/Boullanger Bay wetlands and possible disturbance effects in relation to habitat use and site selection.

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Chapter 5

Spatial and temporal variation of roost use in the Robbins Passage/Boullanger Bay wetlands and south-east Victoria.

Abstract

The aims of this study were to examine seasonal roost use at four sites in the Robbins Passage/Boullanger Bay wetlands by shorebirds and to investigate and compare bi-annual (summer and winter) roost use at Robbins Passage/Boullanger Bay wetlands and two other wetland complexes in southeast Victoria; Werribee and Westernport Bay. Of the four study sites, East Shipwreck Point had the maximum count of species and individuals (19 and 4394, respectively) at any one time, while 90% of the 30 species were observed there over the survey period. Although all roosts were used consistently throughout the 18-month study period, total shorebird abundance and species richness fluctuated over the seasons. The Palaearctic species were present in greater numbers during the summer months, while double-banded plovers were present in greater numbers during autumn and winter. The resident species were generally observed roosting in greater numbers during autumn as compared to summer and spring. These variations reflect the annual migrations of the Palaearctic shorebirds from the Northern Hemisphere and the double-banded plover from New Zealand, while the summer breeding period of the resident shorebirds prevents them from roosting during the summer. The numbers of roosting shorebirds within the three wetland complexes in southeast Australia all varied annually; however, some similarities in these annual variations could be observed among the three areas. There is increasing evidence that an aspect of this co-variation between the three wetland complexes may be due to the movement of juvenile shorebirds.

Introduction

Shorebirds feed on intertidal flats within coastal estuaries and wetlands. When these feeding areas are flooded by the rising tide, the shorebirds move to communal high-tide roost sites, where they can rest, preen and sleep (Hockey, 1985). High-tide roosts can hold 1000s of birds, and be made up of single or multiple species (Burton *et al.*, 1996). Shorebirds tend to use traditional roost sites, returning to the same roost sites year after year. This makes roost studies a useful opportunity to assess and monitor shorebird numbers inter-annually. However, the consistency of roost sites usage may vary over a spectrum, ranging from ephemeral: "used infrequently by few individuals", to traditional: "occupied regularly by large numbers of birds over successive years" with many roosts falling mid-range on this scale (Colwell *et al.*, 2003).

Multi-year studies show that shorebirds exhibit roost site fidelity, and movement that occurs among roosts is usually restricted to a small area (0-15 km) (Rehfisch *et al.*, 2003b). However, this movement does appear to be species-specific, with most species being site faithful to one section of wetland (Symonds *et al.*, 1984; Rehfisch *et al.*, 1996). Pearce-Higgins (2001) found that turnstones (*Interpres* spp.) displayed high roost site fidelity, rarely moving between roosts more than 3km apart, as did oystercatchers (*Haematopus* spp.) (Swennen, 1984). Symonds *et al* (1984) found that while some shorebird species (specifically oystercatchers, turnstones and grey plovers (*Pluvialis squatarola*)) are faithful to a small section, other species (knots (*Calidris* spp.) and dunlin (*Calidris alpina*)) move among sections (> 20km), perhaps in search of better feeding grounds. Thus, the consistency of use of particular roosts may vary considerably under different conditions (Handel & Gill, 1992; Rohweder, 2001) and by different species (Symonds *et al.*, 1984; Rehfisch *et al.*, 1996).

Most species of shorebirds are decreasing on a global scale, as their habitats are destroyed or modified (IWSG, 2003; Rehfisch *et al.*, 2003a). This makes it imperative that we investigate all aspects of shorebird habitat use. The Robbins Passage/Boullanger Bay wetlands in northwest Tasmania are the most important shorebird site in Tasmania, holding more shorebirds than the rest of the state combined (Woehler, 2007). A number of traditional roosts have been identified within the wetlands, however for this study we sought to examine the consistency of use and variability in shorebird numbers and species on a monthly basis. Evidence is also mounting that there is movement of shorebirds between Tasmania and wetland sites in southeast Victoria (e.g. Pied oystercatchers) (S. Lovibond and E. Woehler pers. comm.). The aims of the study were to examine seasonal roost use at four roosts within the Robbins Passage/Boullanger Bay wetlands and also to examine and compare bi-annual (summer and winter) roost use among three wetland complexes; Werribee and Westernport Bay, (both in southeast Victoria), and Robbins Passage/Boullanger Bay wetlands. Two specific questions were addressed:

1. What are the temporal variations of shorebird abundance and species within the four roost sites in Robbins Passage/Boullanger Bay wetlands?
2. Are there any similarities in the temporal variations of shorebird abundance (adult and/or juvenile) among these three wetland complexes?

Method

Study site

The Robbins Passage/Boullanger Bay wetlands are a coastal intertidal system located in the far northwest of Tasmania (40° 40'S, 144° 50'E) with an area of over 100km^2 and an average tidal range of 3.5m (Fig. 1)(DPIWE, 1999a; Dunn, 2000). Approximately 65% of the wetlands is composed of intertidal sand flats, with saltmarsh widespread along the coasts, and sandy and rocky beaches (Dunn, 2000). The wetlands have extensive seagrass beds, considered among the most important in Tasmaniia and are dominated by *Posidonia australis* (Rees, 1993). The extensive intertidal areas provide habitat for resident and migratory shorebirds, with over 25,000 shorebirds recorded in summer, making it the most important shorebird site in Tasmania (Woehler & Park, 2006; Woehler, 2007). Five species of migratory shorebird occur here in internationally significant numbers: curlew sandpipers, double-banded plovers, red-necked stints, red knot and ruddy turnstones; and two resident species occur in nationally significant numbers: pied and sooty oystercatchers (Watts, 1999; Woehler, 2007).

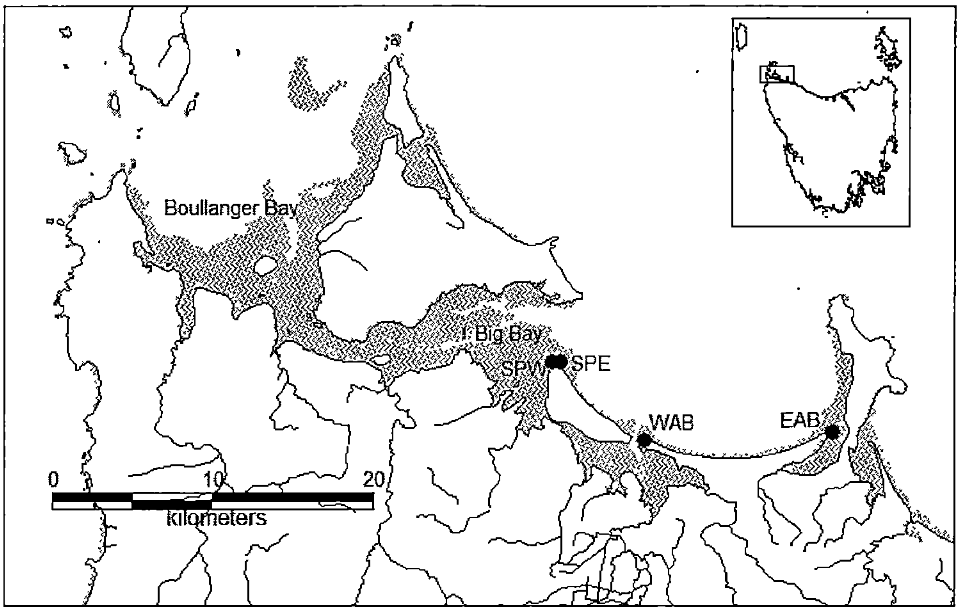

Figure 1. Map of northwest Tasmania showing the location of the four roost sites in the Robbins Passage/Boullanger Bay wetlands. Stippled areas represent tidal flats. (EAB = East Anthony Beach, WAB = West Anthony Beach, SPE = East Shipwreck Point, SPW = West Shipwreck Point)

Roost surveys

Regular surveys of four roost sites were conducted between October 2004 and March 2006 (Fig. 1). At least nine shorebird roosts have been identified throughout the wetlands, but the four study sites were chosen due to their accessibility and safety for a lone worker (Ashby, 1991; Woehler & Park, 2006). Two of the sites were located on Perkins Island, at Shipwreck Point, and referred to as West Shipwreck Pt (WSP) and East Shipwreck Pt (ESP) roosts. These two roosts are on either side of a sandy point, approximately 1km apart, and are considered by Birds Tasmania as a single roost site, but for the purposes of this study were regarded as two separate roosts. The remaining roosts were located on either end of Anthony Beach, a 12km long barrier beach. These roosts were referred to as West Anthony Beach (WAB) and East Anthony Beach (EAB).

Surveys were conducted twice a month between October and March, and monthly between April and September, for the duration of the study. During the surveys, each site was scan sampled (Altmann, 1974) within 2hrs of the predicted daylight high tide, using a 32x *Kowa* TSN-821 spotting scope (Colwell *et al.*, 2003). All shorebird species at the roost were identified and counted. In an attempt to standardise tidal effects, surveys were only undertaken when the high tide was greater than 3.2m. Surveys were not undertaken in persistent rain or in winds greater than 35km/hr.

Birds Tasmania volunteers undertook synchronous summer and winter shorebird counts of at least eight roosts, ensuring there were total shorebird counts for the area in December 2004, February and July 2005 and January 2006, and an extra count in December 2005.

Maximum shorebird abundances and number of species at each roost site were graphed to determine whether there were any inter-seasonal differences (Summer: Dec - Feb, Autumn: Mar - May, Winter: Jun - Aug, Spring: Sept - Nov). Seasonal variation in the maximum abundance of the eight most common species (five residents and three migratory) at all four roost sites was also graphed.

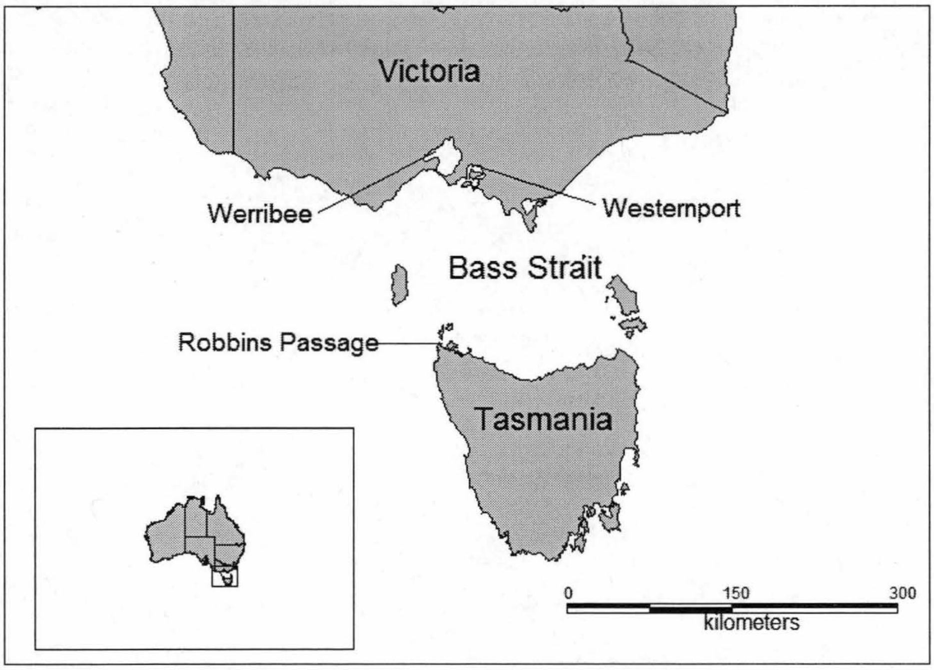

Figure 2: Map of southeast Australia showing the location of the three roost sites in northwest Tasmania and Victoria.

Annual roost surveys

Bi-annual surveys (summer and winter) of traditional shorebird roost sites in southeast Australia have been undertaken by volunteers for a number of years. Birds Tasmania have conducted regular counts of roost sites at the Robbins Passage/Boullanger Bay wetlands since 1993, while Birds Victoria/Australian Wader Studies Group (AWSG) have undertaken counts at two major complexes along the Victorian coastline, Werribee (37° 59'S, 144° 36'E) and Westernport Bay (38° 18'S, 145° 20'E)(Fig. 2). The counts were undertaken on the same day at each complex, to obtain a total count of shorebirds using that area. Within each complex, there were a number of roost sites, but not all roost sites at each complex were counted each year, due to lack of observers. Therefore, to compare the seasonal variation among and within the three complexes, we only used data from roosts that were regularly counted each year. We also analysed winter and summer data separately to enable clearer identification of any seasonal and inter-annual trends. All data analysed were from the period 1993-2005 for all three sites.

Breeding success

The Victorian Wader Study Group (VWSG) have conducted banding catches in south-east Australia during summer since 1979/80. As part of this work, the captured birds were aged, and juvenile/first year birds identified (Minton *et al.*, 2005). This extensive data set has been used by Minton *et al* (2005) to investigate breeding success of migratory shorebirds in the preceding summer in the arctic. Breeding success was expressed as "the percentage of first year birds in the total number of birds caught" (Minton *et al.*, 2005).In an attempt to determine what proportion of migratory shorebirds in northwest Tasmania may be juveniles, the data contained in Minton *et al* (2005) was utilised. The percentage of first year birds caught in south-east Australia between 1993 and 2004 was compared with summer and winter roost counts in northwest Tasmania. This was done for red-necked stint and curlew sandpiper only. For further information on the methodology used for the south-east Australian data, refer to Minton *et al* (2005).

Spearman Rank Correlation Coefficient was used to test for relationships between the variables.

Results

Roost Use

Between 25 and 27 counts were undertaken at each of the four roost sites within the Robbins Passage/Boullanger Bay wetlands over the 18-month period. During the study period, a total of 30 species was recorded, consisting of 17 migratory shorebirds (56%), 5 resident shorebirds (17%), 5 gull and tern species (17%) and 3 other species

(10%: Table 1). ESP had the maximum count of species and individuals (19 and 4393, respectively), while WSP had the least (1 and 6, respectively: Table 2).

Table 1: Species found at each of the four roost sites in the Robbins Passage/Boullanger Bay wetlands and their frequency of occurrence at roosts. EAB = East Anthony Beach, WAB = West Anthony Beach, ESP = East Shipwreck Point, WSP = West Shipwreck Point. (N = 102). Species listed in taxonomic order.

Common name	Frequency of occurrence	EAB	WAB	ESP	WSP
Great cormorant	6	✓		✓	
Pelican	16	✓	✓		
Bar-tailed godwit*	7	✓		✓	
Whimbrel*	1	✓			
Eastern curlew*	10	✓		✓	
Common greenshank*	1			✓	
Terek sandpiper*	3			✓	
Ruddy turnstone*	38	✓	✓	✓	
Great knot*	2			✓	
Red knot*	13			✓	
Sanderling*	6			✓	
Red-necked stint*	68	✓	✓	✓	✓
Sharp-tailed sandpiper*	7		✓	✓	
Curlew sandpiper*	23			✓	✓
Pied oystercatcher	102	✓	✓	✓	✓
Sooty oystercatcher	71	✓	✓	✓	✓
Pacific golden plover*	29		✓	✓	✓
Grey plover*	1			✓	
Red-capped plover	81	✓	✓	✓	✓
Double-banded plover*	48	✓	✓	✓	✓
Lesser sand plover*	7			✓	✓
Greater sand plover*	1			✓	
Hooded plover	87	✓	✓	✓	✓
Masked lapwing	44	✓	✓	✓	✓
Pacific gull	71	✓	✓	✓	✓
Silver gull	65	✓	✓	✓	✓
Caspian tern	28	✓	✓	✓	✓
Crested tern	41	✓	✓	✓	✓
Fairy/Little tern	37	✓	✓	✓	✓
White-faced heron	4	✓			✓

* migratory species

Species Composition

Red-necked stint was the most abundant species (mean = 545 ± 129) and had the greatest number at any roost survey (3280) at ESP in December 2005, with curlew sandpiper the species with the second greatest count (1800), also at ESP in January 2006. Double-banded plover was the third-ranked species in abundance (720), at WAB in July 2005. Pied oystercatcher were the most frequently observed shorebird, found at every roost survey over the 18 months, with hooded plover and red-capped plover the second and third, respectively (Table 1). A number of species were seen on only one occasion, such as whimbrel and grey plover. Twenty-seven of the 30 species (90%) were observed at ESP at some time over the survey period, 63% were observed at EAB and only 53% of all species were seen at both WAB and WSP. All the migratory species, excepting whimbrel, were found at ESP, while only five species were found at WSP and WAB.

Table 2: Maximum, minimum and mean roost counts for each site and the date of occurrence.

Roost	No. of counts	Min count	Date min count	Max count	Date max count	Mean count	Mean no. of species
East Anthony Beach	25	166	18 Oct 2004	866	10 Feb 05	434.44	10.2
West Anthony Beach	26	83	26 Oct 2004	1194	10 Mar 2005	391.46	6.7
East Shipwreck Point	27	116	28 Nov 2004	4393	8 Feb 2006	2623 63	13.4
West Shipwreck Point	24	6	12 Dec 2004	273	17 Oct 2004	56.33	5 2

Seasonal variation

All four sites within the Robbins Passage/Boullanger Bay wetlands were used throughout the year, although abundance and species richness fluctuated greatly (Fig. 3). Roosting species richness was highest during the summer, as was total shorebird abundance. All four sites displayed some variation in shorebird abundance and number of species over the 18-month period (Fig. 4).

The seasonal variation for the eight shorebird species is shown in Figure 5. The Palaearctic species were present in greater numbers during the summer months than during the winter months, while double-banded plovers, a migratory species from

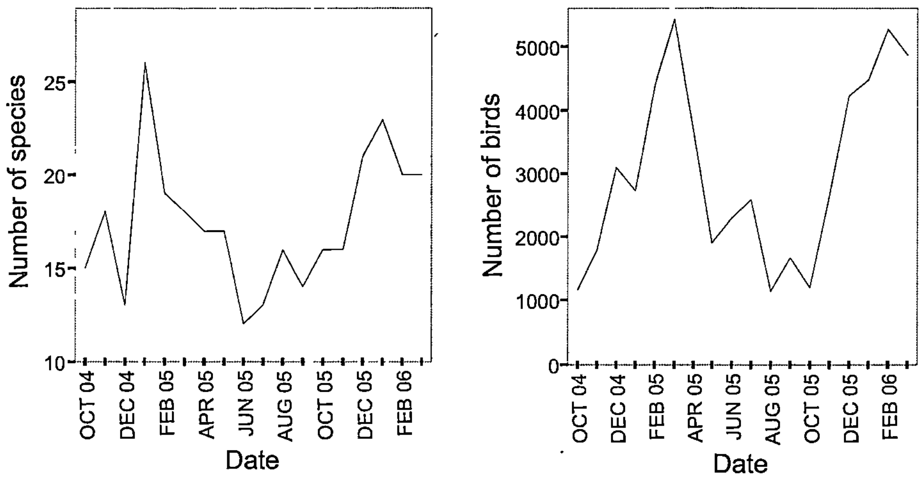

Figure 3: Total numbers of shorebird species and shorebirds at all four roost sites in the Robbins Passage/Boullanger Bay wetlands over the 18-month period.

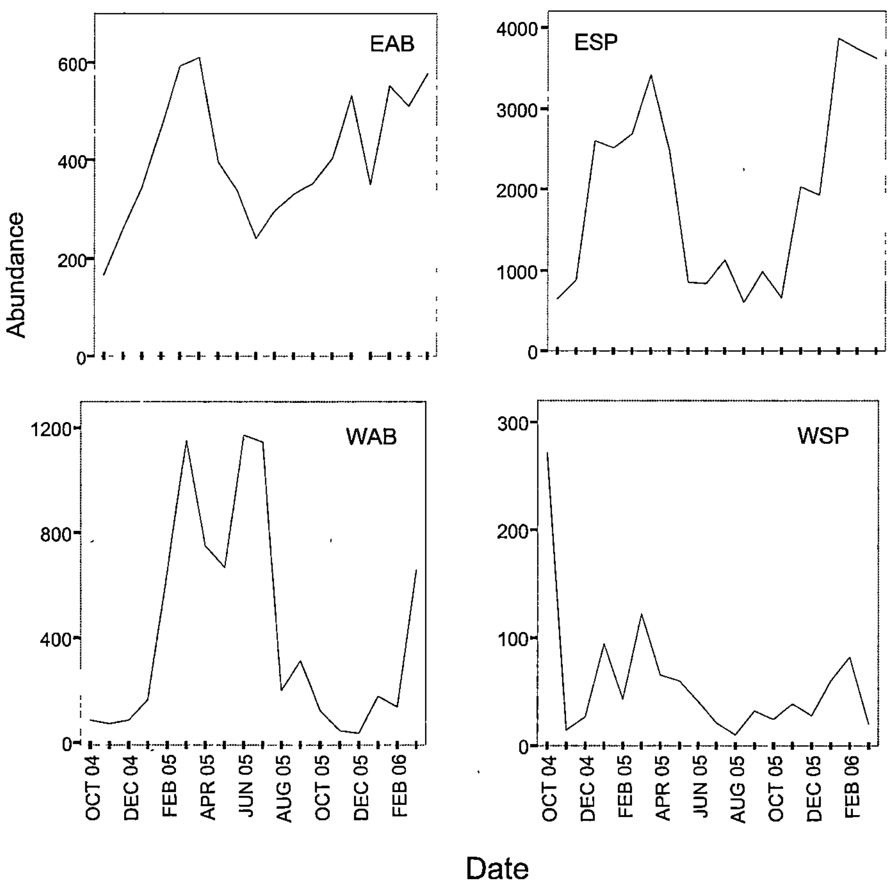

Figure 4: Mean total number of shorebirds at each site for each month over an 18 month period. EAB = East Anthony Beach, WAB = West Anthony Beach, ESP = East Shipwreck Point, WSP = West Shipwreck Point.

New Zealand, were found at the roost sites in greater numbers during autumn and winter. The resident shorebird species, red-capped plover, pied oystercatcher and sooty oystercatcher, were all observed at roost sites in greater numbers during autumn, and lesser numbers during summer and/or spring.

Annual roost use

The Victorian roost sites had considerably higher total numbers of shorebirds than did those in northwest Tasmania. The mean summer count totals for Werribee and Westernport were 14,310 (± 3296) and 11,532 (± 2762), respectively, whereas Robbins Passage/Boullanger Bay wetlands (RPW) had 3621 (± 2416). The mean number of species was also greater at the Victorian sites (Werribee = 20.6, Westernport = 17, RPW = 11.7) (Table 3). However, despite these numerical differences, similar patterns were observable in the numbers of shorebirds at the three wetlands over the 12 year data set (Fig. 6). During the summer, the two Victorian sites were almost mirror images of each other, with one site having lower roost totals when the other site had greater roost totals, strongly suggesting that birds were moving between these two alternative sites ($R = -0.58$, $p = 0.06$). Some of these peaks and dips in numbers of shorebirds at Victorian roosts, coincided with peaks and dips in roost totals in RPW, although not significantly. This can be clearly seen during 2002 to 2004, with Westernport and RPW both having high numbers of shorebirds, and then both dipping to their lowest roost totals over the 12 years between 1993 and 2005, while Werribee had its greatest roost totals. In 2004, Werribee roost totals decreased, and RPW and Westernport roost numbers increased. At the Victorian sites the winter counts were significantly correlated, with coinciding increases and decreases in shorebird numbers during the 1990s ($R = 0.76$, $p < 0.05$).

When comparing data trends for common shorebird species over the three sites, some similarities were apparent, although there were no significant correlations (Figs. 7 & 8). Of the six species analysed in this study, four were Palaearctic shorebirds, one a migratory species from New Zealand and one resident shorebird. During the summer counts, three of the Palaearctic species, curlew sandpiper, Pacific golden plover and red-necked stint, showed similar trends among the three sites in their roost counts (Fig. 7). In the mid-1990s, numbers of curlew sandpipers showed opposing patterns at Werribee and RPW, with one site having increased numbers when the other site had decreased numbers of curlew sandpipers. Pacific golden plover roost totals in the late-1990s, showed simultaneous high numbers at the Victorian sites and low numbers at RPW and two years later, high numbers at RPW and lower numbers at the Victorian sites.

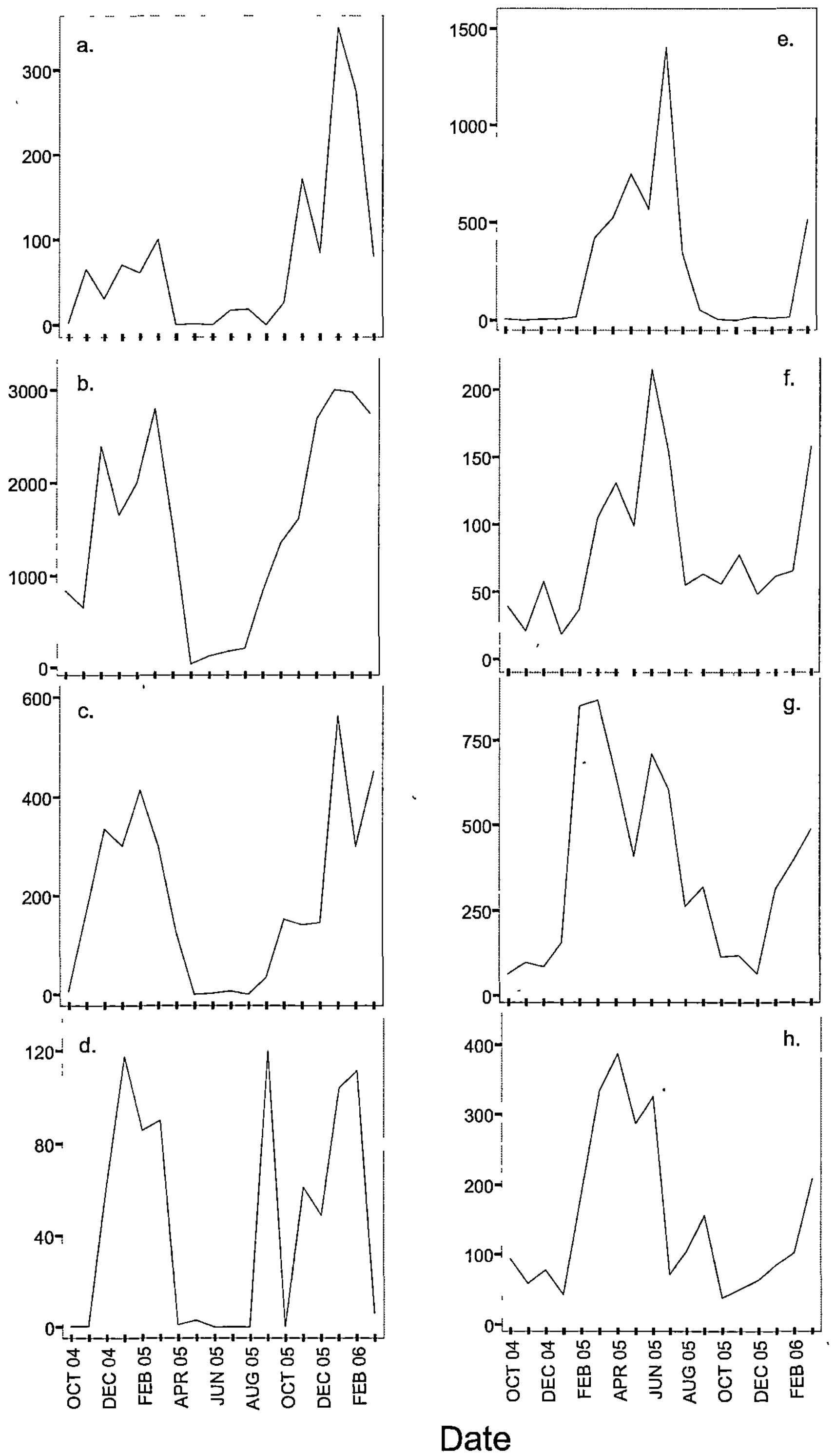

Figure 5: Total numbers of eight species of shorebirds at all four roost sites at the Robbins Passage/Boullanger Bay wetlands, for each month over an 18-month period. a. curlew sandpiper, b. red-necked stint, c. ruddy turnstone, d. pacific golden plover, e. double-banded plover, f. red-capped plover, g. pied oystercatcher, h. sooty oystercatcher.

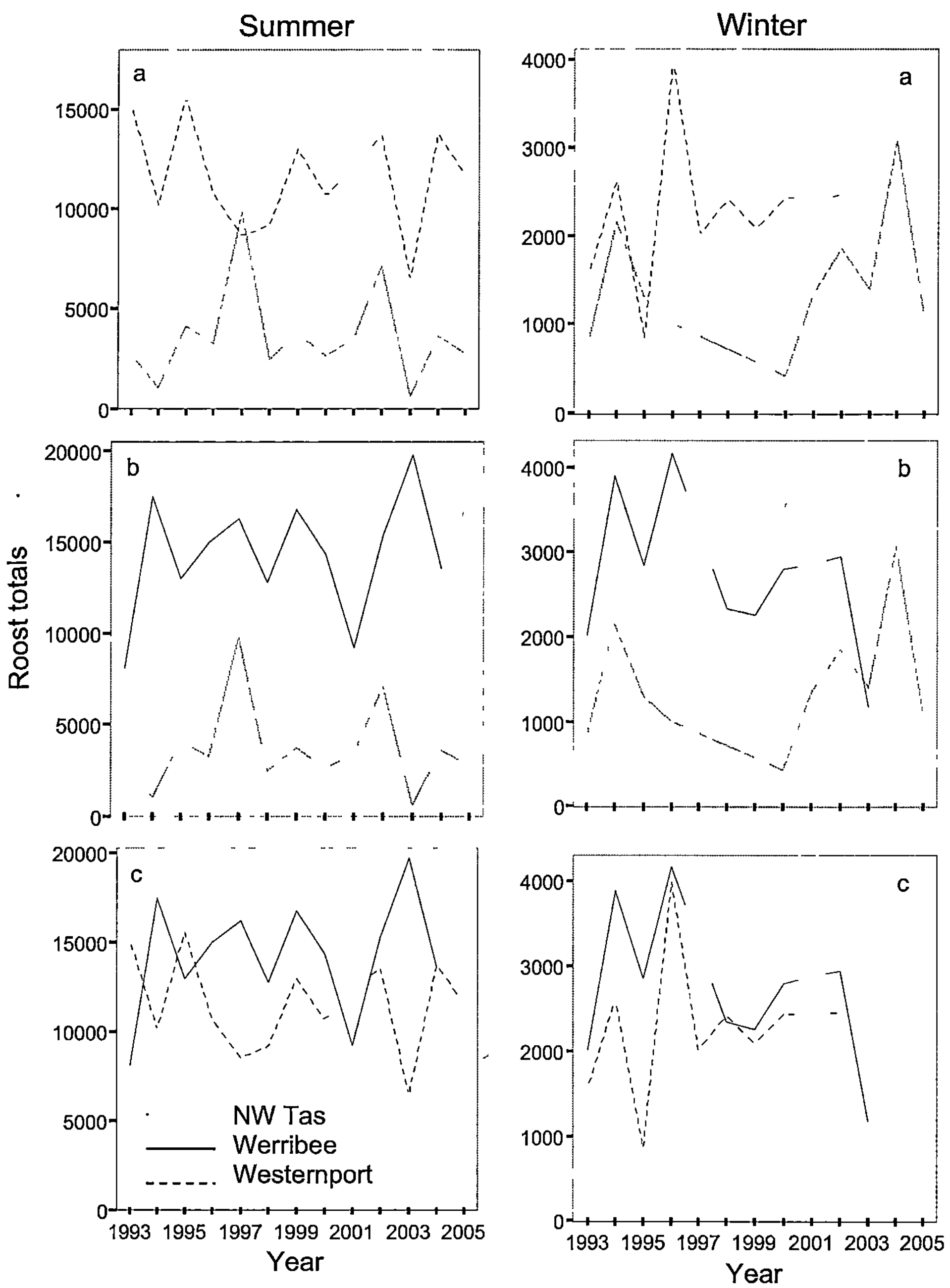

Figure 6: Total number of shorebirds at regularly counted roosts at three sites in Victoria and Tasmania during summer and winter. The gaps represent years when counts were not undertaken at those particular roosts. a = Westernport and northwest Tasmania, b = Werribee and northwest Tasmania, c = Westernport and Werribee.

From 2002-2004, patterns could be seen in the numbers of red-necked stints at the three sites, with similar numbers at each site during 2002, a sharp increase at Werribee during 2003, with consequent decreases at the other two sites, and then Westernport and RPW increasing the following year, while the number at Werribee decreased. There were few similarities in the pied oystercatcher roost totals, although an increase in numbers could be seen at RPW and Westernport in 1995, and then both sites decreased simultaneously in 2003.

Patterns could still be observed in the winter counts, although the numbers of some species were lower (Fig. 8). Double-banded plover were found at all three sites, with similar numbers at each site during the mid-1990s. However, the following five years showed a decrease in numbers in RPW and Werribee, and a subsequent increase at Westernport. As the roost totals for double-banded plovers decreased over the next two years at Westernport, numbers showed an increase at RPW. In 1995, curlew sandpiper showed high numbers at Werribee and low numbers at Westernport one year, then high numbers at Westernport and low numbers at Werribee the next year. The greatest numbers of red-necked stints were found at both Victorian sites in 1996, with both sites showing a sharp decrease the following year.

Breeding Success

The percentage of first year red-necked stints and curlew sandpipers caught in south-east Australia is plotted against summer and winter roost counts in northwest Tasmania (Fig. 9). The lack of winter roost counts from 1997 to 1999 makes it difficult to see a long-term pattern, especially for curlew sandpiper. However, while there is no significant correlation between percent of first years in south-east Australia and the winter or summer population in northwest Tasmania, there is an observable pattern in the early-mid 2000's for red-necked stints. The summer of 2002 and 2004 both had a higher than average percent of first years in the red-necked stint population (34.5% and 23% respectively, mean = 18%). This is reflected in the winter (850 and 1200 birds respectively) and summer (6000 and 3000 birds respectively) roost counts for northwest Tasmania, which were also greater than average (mean = 392 in winter and 2006 in summer). In summer 2003, red-necked stint counts were below average in northwest Tasmania (428), as was Westernport (4061, mean = 5970), while Werribee had greater than average numbers of red-necked stint (13,642, mean = 7278) (Fig. 7).

It is also notable that a 50% decrease in the average number of red-necked stints in northwest Tasmania during the summer of 1998 coincides with a lower than average percentage of first year birds (7.8%). Curlew sandpiper showed a 51% decrease in average numbers for the 1999 summer counts. This coincides with a lower than average percentage of first year birds (4.1%, mean = 13%) in the south-east Australian summer populations

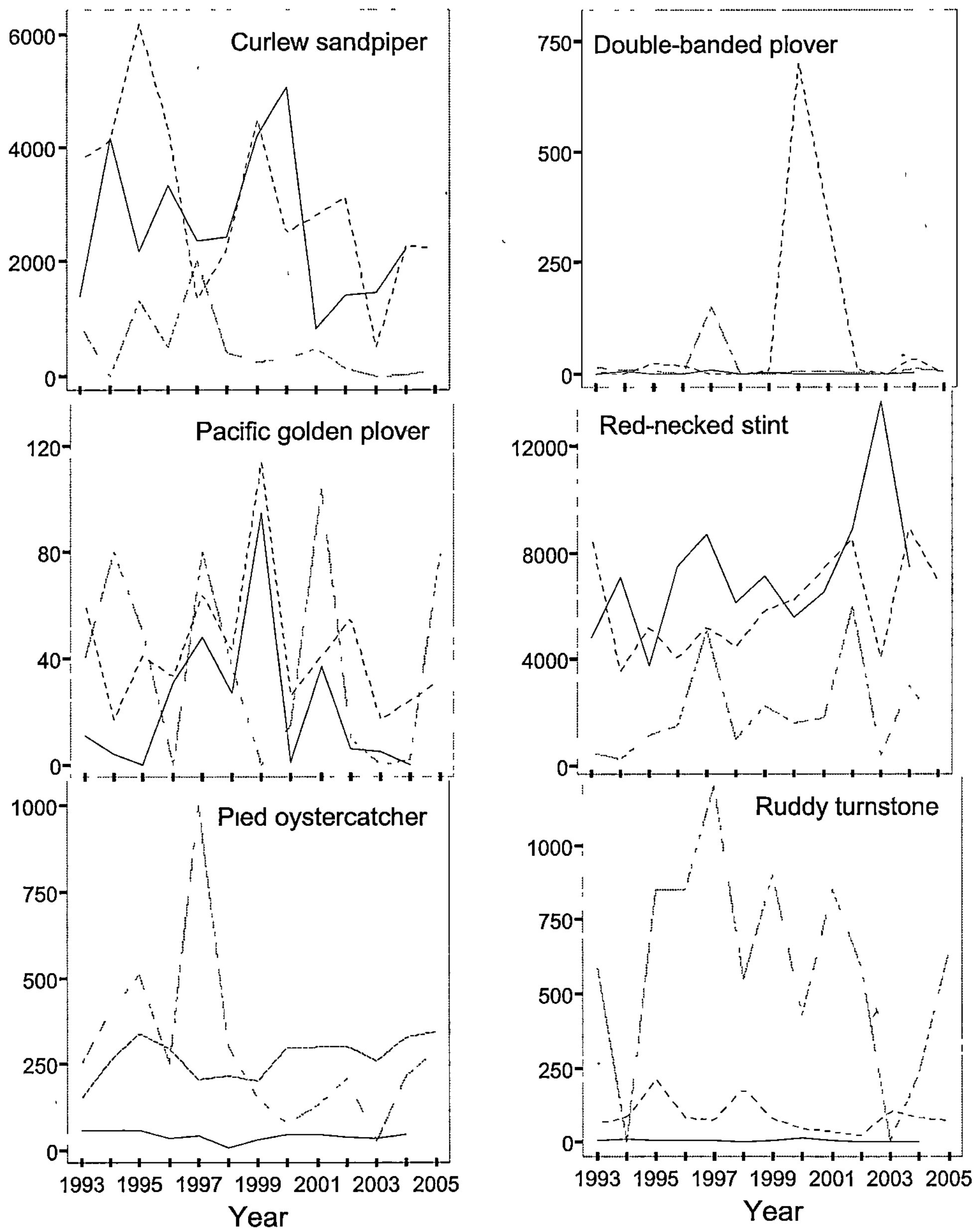

Figure 7: Total numbers of shorebirds for each species at regularly counted roosts at three sites in Victoria and Tasmania during summer. Werribee solid line, Westernport dashed line, NW Tasmania dotted line.

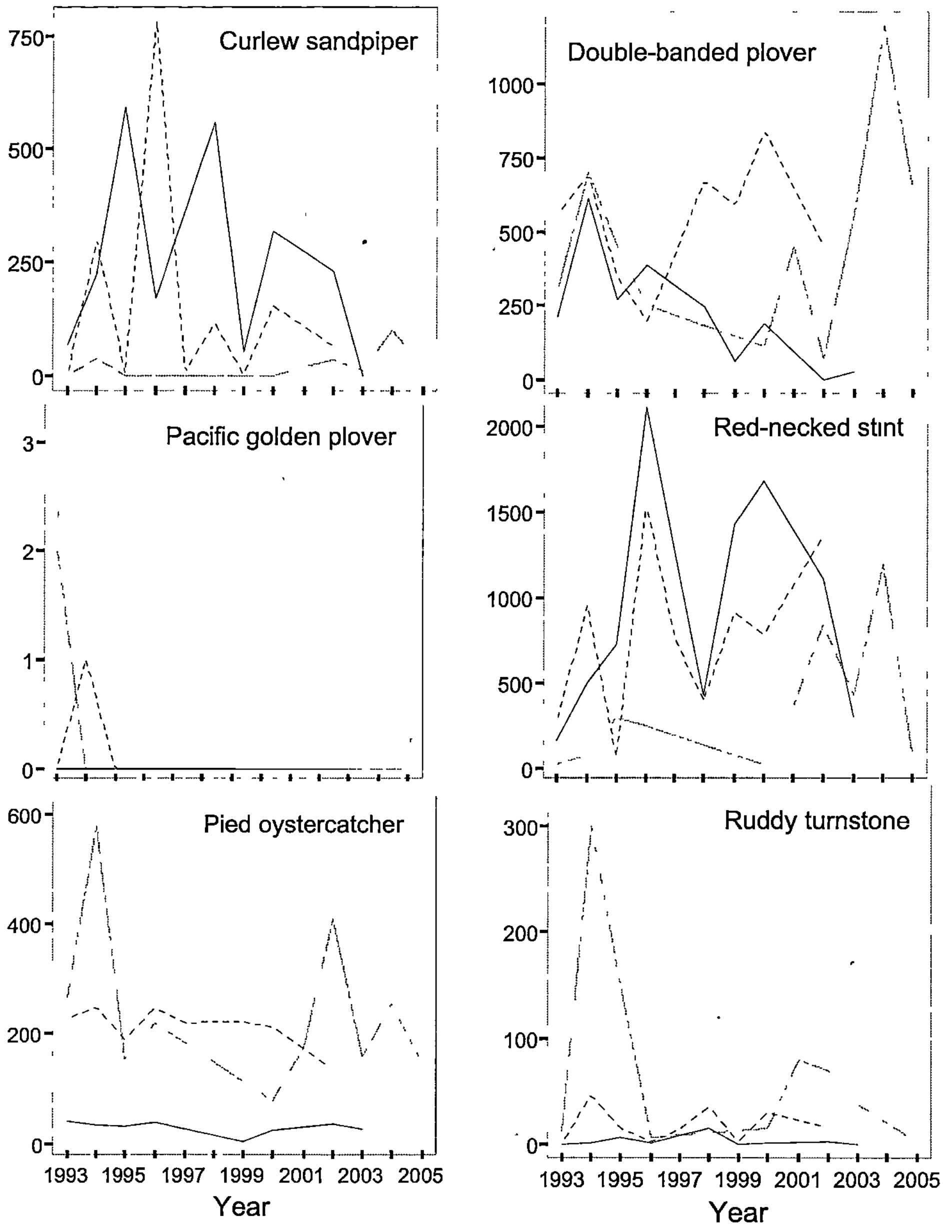

Figure 8: Total number of shorebirds for each species at regularly counted roosts at three sites in Victoria and Tasmania during winter. Werribee solid line, Westernport dashed line, NW Tasmania dotted line.

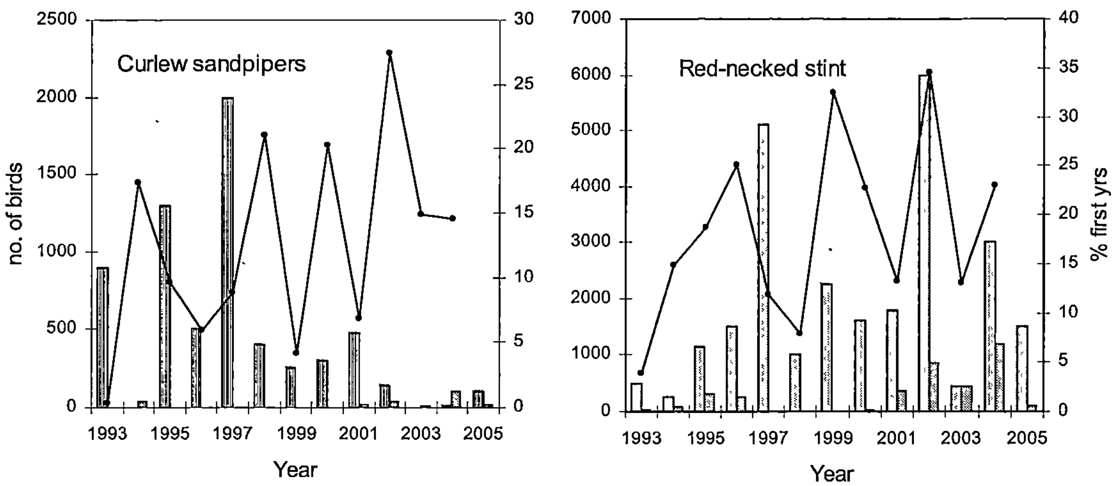

Figure 9: Total number of curlew sandpiper and red-necked stint in NW Tasmania during summer and winter and percentage of first year curlew sandpiper and red-necked stint caught in south-east Australia. Summer hatched bars, Winter solid bars, % first years solid line.

Discussion

Seasonal variation

It is a widely-held belief that shorebirds use traditional roost sites (Hale, 1980; Rehfisch *et al.*, 1996; Warnock & Takekawa, 1996; Leyrer *et al.*, 2006), and thus some of these sites have been used to monitor shorebird numbers over time (e.g. Burton *et al.*, 1996). The roost sites studied in Robbins Passage/Boullanger Bay wetlands were all used throughout the year, however all of the sites showed variations in shorebird abundance over the 18-month study period.

Seasonal variation in roost use may be explained by a combination of two factors: migration and breeding phenologies (Hockey, 1985; Colwell *et al.*, 2003). Migration is the annual movement of particular shorebirds between their breeding and non-breeding (wintering) areas (Lane, 1987). In the case of RPW, this refers to Palaearctic migrants which travel from their breeding grounds in Siberia and Alaska, through the East Asian-Australasian Flyway (EAAF) to Australia and New Zealand (Priest *et al.*, 2002). This contributes to the variation in shorebird numbers at ESP, and to a lesser extent, EAB and WSP, which all show higher numbers of shorebirds during summer, when the Palaearctic shorebirds are present. The Palaearctic migrants arrive from their breeding grounds between September and December and depart throughout February to April. A number of Palaearctic migrants are present throughout the year, and these are juveniles which are known to spend the whole year in Australia, returning to their

Table 3: Species found at each of the three roost sites in southeast Australia between 1993-2005. RPW = Robbins Passage/Boullanger Bay wetlands. Species listed in taxonomic order.

Common name	Scientific name	RPW	Westernport Bay	Werribee
Latham's/Japanese snipe*	*Gallinago hardwickii*	✓		✓
Black-tailed godwit*	*Limosa limosa*			✓
Bar-tailed godwit*	*Limosa lapponica*	✓	✓	✓
Whimbrel*	*Numenius phaeopus*	✓	✓	
Eastern curlew*	*Numenius madagascariensis*	✓	✓	✓
Marsh sandpiper*	*Tringa stagnatilis*			✓
Common Greenshank*	*Tringa nebularia*	✓	✓	✓
Wood sandpiper*	*Tringa glareola*			✓
Terek sandpiper*	*Xenus cinereus*	✓	✓	
Common sandpiper*	*Actitis hypoleucos*		✓	✓
Grey-tailed tattler*	*Heteroscelus brevipes*	✓	✓	✓
Ruddy turnstone*	*Arenaria interpres*	✓	✓	✓
Great knot*	*Calidris tenuirostris*	✓		
Red knot*	*Calidris canutus*	✓	✓	✓
Sanderling*	*Calidris alba*	✓		
Red-necked stint*	*Calidris ruficollis*	✓	✓	✓
Pectoral sandpiper*	*Calidris melanotos*	✓		✓
Sharp-tailed sandpiper*	*Calidris acuminata*	✓	✓	✓
Curlew sandpiper*	*Calidris ferruginea*	✓	✓	✓
Broad-billed sandpiper*	*Limicola falcinellus*			✓
Ruff*	*Philomachus pugnax*			✓
Red-necked phalarope*	*Phalaropus lobatus*			✓
Pied oystercatcher	*Haematopus longirostris*	✓	✓	✓
Sooty oystercatcher	*Haematopus fuliginosus*	✓	✓	✓
Black-winged stilt	*Himantopus himantopus*			✓
Banded stilt	*Cladorhynchus leucocephalus*			✓
Red-necked avocet	*Recurvirostra novaehollandiae*		✓	✓
Pacific golden plover*	*Pluvialis fulva*	✓	✓	✓
Grey plover*	*Pluvialis squatarola*	✓	✓	✓

Common name	Scientific name	RPW	Westernport Bay	Werribee
Red-capped plover	*Charadrius ruficapillus*	✓	✓	✓
Double-banded plover*	*Charadrius bicinctus*	✓	✓	✓
Lesser sand plover*	*Charadrius mongolus*	✓	✓	✓
Greater sand plover*	*Charadrius leschenaultii*	✓	✓	
Black-fronted dotterel	*Elseyornis melanops*	✓		✓
Hooded plover	*Thinornis rubricollis*	✓		
Red-kneed dotterel	*Erythrogonys cinctus*			✓
Banded lapwing	*Vanellus tricolor*	✓		✓
Masked lapwing	*Vanellus miles*	✓	✓	✓

* migratory species

breeding grounds in their second year to breed (Lane, 1987; Minton *et al.*, 2004). The peak in shorebird numbers during autumn at WAB is due to double-banded plovers, which are a migratory species from New Zealand. They breed in New Zealand during the summer and migrate to Australia for the February to September period.

Unlike the Palaearctic species, the resident shorebirds were observed at the Robbins Passage/Boullanger Bay wetland roost sites in greatest numbers during autumn. Their absence from the roost sites during the spring and summer is due to their behaviour during the breeding seasons, when the adult shorebirds are mating, incubating eggs, and protecting chicks (Lane, 1987). Oystercatchers and red-capped plovers breed between October and January (Pringle, 1987). After the breeding season they return to the communal roost sites during the high tide period.

These two factors, migration and breeding, account for the seasonal variations in shorebird abundances at the roost sites. There is however, another source of variation that is not seasonal but can affect the daily roost use of an area. The height of the tide influences shorebird roost use, by either making the roost unavailable or by allowing the birds to continue feeding (Hockey, 1985). Spring tides, when the tidal range is at its maximum, can cover some roosts not normally flooded at other times, forcing shorebirds to roost elsewhere (Burton *et al.*, 1996). More commonly however, especially on neap tides, when the tidal range is minimal, not all of the shorebird population joins the roost, as there may be feeding areas still available or the birds may roost temporarily on sites not normally used at high tide (Colwell *et al.*, 2003).

This could be a factor in the Robbins Passage/Boullanger Bay wetlands, especially if shorebirds are roosting on exposed sand bars during neap tides, as has been observed (F. Spruzen pers. obs.)

The results from this study clearly indicate that some sites are more frequently used than others, with migrant shorebirds displaying particular preferences for certain roosts in the Robbins Passage/Boullanger Bay wetlands. It has been proposed that the size (with respect to the numbers of birds present) of the roost is dependent on the size and quality of the nearest foraging area, and that the larger roost sites have the higher-quality birds (Swennen, 1984). The role of roost site choice by shorebirds is starting to be examined and researchers agree that distance to feeding areas is one of the main determinants of roost site selection for shorebirds (Rehfisch *et al.*, 2003b; Rogers *et al.*, 2006a; Spruzen *et al.*, submitted). Disturbance and risk of predation are also thought to be contributing factors (Luis *et al.*, 2001; Rosa *et al.*, 2006). If a roost is regularly disturbed, the shorebirds may be forced to find an alternative site (Mitchell *et al.*, 1988; Burton *et al.*, 1996).

Although the main feeding areas in the Robbins Passage/Boullanger Bay wetlands have not yet been identified, they are thought to be to the west of Perkins Island, as this is where the most extensive areas of tidal flats are present. Two of the roost sites examined in this study (ESP and WSP) are on an island only accessible at low tide, or by boat at other times. The remaining two sites are on either end of a popular local beach, where horse-riding and recreational four-wheel driving is common (Spruzen, 2005). Thus, of the study sites examined here, the roosts at Shipwreck Point are both less disturbed and probably closest to the primary feeding areas in the wetlands. West Shipwreck Pt is a small section of beach, 40m wide and only 50m from tall cover (vegetation > 2m). East Shipwreck Pt is located on a point, with beach extending on either side. The roosting site is 110m wide and 175m from tall vegetation cover. In a shorebird roost model developed by Spruzen *et al* (submitted) (Ch 6) for these wetlands, shorebirds selected wider sites for roosts, which was correlated with increasing distance to tall cover. Tall cover may act as cover for predators such as raptors, therefore the greater the distance between the roost and the potential cover, the more time the shorebirds may have to react to an approaching predator (Rogers, 2003). The model therefore supports the finding that ESP is the more optimal roost site, with the greatest shorebird abundance.

Annual patterns

The three wetland complexes in southeast Australia examined in this study all showed variations in shorebird numbers on an annual scale, with some of the variations displaying common patterns in their summer and, to a lesser extent, winter shorebird roost counts. These annual variations can be influenced by three variables: local conditions, conditions in other areas used *en route*, and fluctuations in the entire population (Lambeck *et al.*, 1989). Changes in local conditions would involve the loss or modification of habitats, either roosting or feeding. As far as we are aware there has been no substantial change at these three complexes since 1993.

The three wetland complexes are all at the southern end of the EAAF, one of eight migratory shorebird routes around the world. These migratory shorebirds travel great distances and during their migration they stop off at a number of wetland staging sites to 'refuel' and regain sufficient energy to continue their migration. For the EAAF, many of these staging sites are in countries such as China and South Korea, which have reclaimed 37% and 43% of their wetlands and intertidal areas, respectively, and more than 80% of significant wetlands within east and south-east Asia area currently under threat, predominately through agricultural expansion (Barter, 2002; Birdlife International, 2004a). Loss of stopover sites can therefore seriously affect annual shorebird abundances. While this is definitely an issue for shorebird survival, this study has only investigated the shorebird abundance of particular roosts within each complex. These numbers do not show an overall decrease in total shorebird abundance over the 12 years for which data are available, which would be expected if the major stopover sites were unavailable. However, it has been noted that numbers of curlew sandpipers have been decreasing nationwide, especially southern Australia, and this is reflected in our data (Figs. 8 & 9) (Olsen *et al.*, 2003; Olsen & Weston, 2004; Gosbell & Clemens, 2006; Wetlands International, 2006). To confidently monitor population trends over time would require consideration of the whole roosting complex.

A more feasible cause of the annual variation in this case, is inter-annual fluctuations in the shorebird populations as a result of breeding success and survival. Annual breeding productivity of shorebirds may be estimated by the proportion of juveniles in catches at their wintering sites (Underhill *et al.*, 1989). Winter counts can also be a good indicator of breeding success as many of the juveniles do not return to their breeding grounds until they are 2-3 years old (Minton *et al.*, 2005; Harebottle *et al.*, 2006). A study in South Africa used winter counts of Palaearctic shorebirds to assess breeding productivity and thereby monitor population changes (Harebottle *et al.*, 2006). Studies in south-east Australia went a step further and attempted to monitor shorebird breeding productivity by measuring the proportion of first year birds in austral summer banding catches, with good results (Minton *et al.*, 2004; Minton *et al.*, 2005). The percentage of first year birds in the total catch is an index of breeding success for the previous breeding season in the arctic. Minton *et al* (2005) found a strong correlation (R = 0.85) between the percentage of first year red-necked stint in summer catches in south-east Australia and winter population counts. The winter counts of this species are therefore a good indication of the previous years breeding success in the arctic. Minton *et al* (2005) also found a good correlation for curlew sandpiper, although not as strong as red-necked stint.

The current study found that numbers of red-necked stint in northwest Tasmania increased in the summer and winter of 2002 and 2003, with numbers greater than average for red-necked stint. This is in line with the greater than average percentage of first year red-necked stints caught in south-east Australia. There was also a decrease in red-necked stints in northwest Tasmania during the summer of 1998, while curlew sandpiper showed a sharp decrease in summer 1999, both coinciding with a lower than average percentage of first year birds in the south-east Australian summer populations (Minton *et al.*, 2005). Therefore, the austral winter, and to a lesser extent summer, populations of red-necked stints and curlew sandpipers in northwest Tasmania may give an indication of the breeding success in the arctic for the preceding summer.

However, it is worth noting that the increased numbers of red-necked stints in northwest Tasmania in 2002 did not result in a large number of red-necked stints in the following year, when the number of red-necked stints was actually a quarter of the average. So where did they go? Westernport also had lower than average numbers, while Werribee had over 13,000 red-necked stints present over summer, nearly double the average (Fig. 7 & 9). It seems likely that this is where the birds from Tasmania moved to. That summer, there were also very low numbers of curlew sandpipers, Pacific golden plovers and ruddy turnstones at all sites. The low numbers of these species may have allowed the majority of stints to roost at Werribee, suggesting that this may be the preferred site for whatever reasons. This resulted in lower than usual numbers at the remaining two complexes. Some of the migrating shorebird species were observed roosting in RPW in greater numbers than in Victoria, e.g. Pacific golden plovers and ruddy turnstones. This may be due to the fact that all the prime positions in Victoria were taken by red-necked stints, curlew sandpipers and other species, which arrived earlier and forced the remaining species farther south, or these species have different habitat requirements which are found in RPW.

This information begins to suggest that there is movement among the three complexes between years. Abundance at the two Victorian complexes appear to be interrelated, with one complex having high numbers of shorebirds when the other site has low numbers, although they also display increases and decreases in shorebird numbers simultaneously. The same can also be said for the RPW, which sometimes has a similar pattern to Westernport Bay, in Victoria, but at other times is displaying an opposite trend to the Victorian complexes. These patterns have also been noted by Gosbell and Clemens (2006) in their analysis of 25 years of Australian shorebird population data.

Several tracking studies have been conducted on shorebirds to determine roost movements (Mitchell *et al.*, 1988; Rehfisch *et al.*, 1996; Warnock & Takekawa, 1996; Conklin & Colwell, 2007), and there is general agreement that once the shorebirds reach their wintering grounds, they are faithful to that area, only moving short distances between roosts, if at all. Conklin and Colwell (2007), found that dunlin had a very high site fidelity to their wintering grounds, but low fidelity to the primary roost sites. The distance between the Victorian complexes (approximately 60km) and the RPW (approximately 300km) is far beyond the scale of inter-roost movements discussed in these studies (< 20km). The Tasmanian site is an additional 'flight' after a 10,000km+ migration. It therefore seems unlikely that adult shorebirds that normally roost at a certain complex, would switch to another complex the next year. It seems more probable that the fluctuations are the result of the dispersal of juvenile shorebirds, which may not display high site fidelity for the first 1-2 years. The 2003/2003 counts of red-necked stint support this idea, with juveniles moving between sites for the first 1-2 years, before finding a permanent wintering site.

This study raises many questions and opportunities for further study. Investigations into possible movements among the three roost complexes would involve mark-recapture/leg flagging studies to determine whether shorebirds marked at one site were observed at one of the other sites in subsequent years. This method could also be used to investigate inter-roost movements within the Robbins Passage/Boullanger Bay wetlands, although radio tracking would be very useful. Radio tracking would also enable the identification of primary feeding areas within the Robbins Passage/Boullanger Bay wetlands. Comparing the proportion of juveniles and adults of each species roosting at each wetland site would provide more information on the habitat requirements for each species and shorebirds as a whole and allow the estimation of breeding success through the proportion of juveniles caught each year.

It is clear that shorebirds do use traditional roost sites and this study has verified previous findings that roost use varies on seasonal and annual temporal scales (Colwell *et al.*, 2003; Peters & Otis, 2007). Therefore, in an effort to monitor shorebird abundance, researchers must count the entire complex, not just selected roost sites. The fact that the shorebirds have definite species-specific preferences for certain roosting sites and may display high site fidelity for these sites, emphasises the importance of these areas to shorebird conservation and management.

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Chapter 6

High-tide shorebird roost choice in temperate coastal Australia.

Abstract

Shorebirds move between their low tide feeding areas and high tide roost areas, both habitats being essential for their survival. However, these habitats are threatened by a variety of human activities. Before we can adequately protect and manage roosts, we must understand why they are selected by shorebirds. Studying roost habitat choice in shorebirds in the Robbins Passage/Boullanger Bay wetlands involved identifying and measuring seven variables at roost (n=9) and non-roost (n=23) sites throughout the wetlands. Through principal component analysis and univariate analysis, these variables were reduced to three: DISTANCE TO FEEDING AREA, DISTANCE TO ROAD and WIDTH (width of site). DISTANCE TO FEEDING AREA and WIDTH were identified by a logistic regression model as the primary variables influencing shorebird roost site selection, with an overall classification success rate of 87.5%. An independent data set from south-east Tasmania was used to evaluate the model (classification success: 91.3%) and the area under the receiver operating characteristic curve showed that the model had excellent discriminatory ability (98%). By reducing the linear distance between roost and feeding areas, the shorebirds minimise energy expenditure during commuting. The choice of wider sites (i.e. shallower slope) allows more birds to roost there, leading to increased predator vigilance, and a decrease in energy spent on thermoregulation through flocking. Wider sites also allow the shorebirds to roost farther from tall cover; DISTANCE TO TALL COVER and WIDTH were significantly correlated ($r = 0.6$). Further work is necessary to improve the model, but it provides enough information to initiate appropriate management and conservation strategies for the Robbins Passage/Boullanger Bay wetlands and other temperate wetlands.

Introduction

Migratory shorebirds typically spend non-breeding periods in coastal wetlands, far from their breeding grounds. At low tide, they move over the intertidal flats to feed on invertebrate prey, and during the high tide (when their feeding areas are unavailable), they move to high-tide areas where they gather in congregations known as roosts (van de Kam *et al.*, 2004). Both of these low and high tide habitats are essential for the survival of all shorebirds, resident and migratory. However, wetlands are presently amongst the most impacted and degraded of all habitats, due to draining, infilling, pollution and overexploitation of their resources (Young *et al.*, 2001). There is currently much effort underway towards the restoration and conservation of wetlands in Australia and around the world (Finlayson & Rea, 1999; Young *et al.*, 2001).

Habitat loss and degradation are among the main threats facing shorebirds, arising from increased coastal development and human population. In some areas, decreases in shorebird populations have been linked to disturbance or loss of shorebird roost or feeding sites (Mitchell *et al.*, 1988; Pfister *et al.*, 1992; Burton *et al.*, 1996). In order to conserve or replace the habitat requirements of shorebirds, there is a need to understand the birds' specific requirements in coastal habitats. Habitat suitability models can provide information about the ecological needs of shorebird species, and help us to ensure that these needs are met for the future conservation and management of the species through appropriate management regimes.

Shorebirds use traditional roost sites, that is, they regularly use the same area over successive years (Colwell *et al.*, 2003). But what makes such a site attractive as a roost? A variety of factors have been proposed, such as: shelter from exposure (Handel & Gill, 1992; Rehfisch *et al.*, 2003b), size (area) of roost (Peters & Otis, 2007), proximity to feeding areas (Furness, 1973; Rogers *et al.*, 2006a), lack of disturbance (Furness, 1973; Luis *et al.*, 2001; Rohweder, 2001), and lack of predation risk (Rehfisch *et al.*, 2003b; Rosa *et al.*, 2006). These factors can be classified in two broad categories: 1) energy expenditure, and 2) predation risk. Energy expenditure of shorebirds is related to the daily cost of flying to and from feeding areas; disturbance, as the shorebirds will typically take flight when disturbed, using valuable energy resources; and thermoregulation through daily exposure to the elements, mainly wind, although heat stress may be a problem in warmer climates (Rogers *et al.*, 2006a). The risk of predation is related to roost size, and the size of the flock that may roost there, which may then influence thermoregulatory and vigilance behaviours. The risk of predation may also be influenced by the distance of the roost from tall cover, as tall cover may act as cover for potential predators (Rogers *et al.*, 2006a). To date, only two attempts have been made to quantify the effect of these factors on roost site selection, neither in temperate Australia (Rogers *et al.*, 2006a; Peters & Otis, 2007).

Predictive modelling of a species distribution and quantifying it in relation to environmental variables is becoming more popular, and accepted as a way to avoid the expensive and time-consuming surveys otherwise required (Franco *et al.*, 2000; Jaberg & Guisan, 2001; Gibson *et al.*, 2004). Logistic regression is the most frequently used modelling technique in species distribution modelling, due to the relative ease of collecting presence-absence data (Rushton *et al.*, 2004).

The Robbins Passage/Boullanger Bay wetlands in north-west Tasmania are listed as a nationally important wetland and are the most important shorebird area in Tasmania (Young *et al.*, 2001; Woehler & Park, 2006). The wetlands support over 25,000 shorebirds of 23 species during the summer months, and the area is one of the most southerly feeding grounds for shorebirds using the East Asian-Australasian Flyway (Dunn, 2001; WWF-Australia, 2004; Woehler & Park, 2006). This study aims to use logistic regression models to quantify shorebird roost choice in the Robbins Passage/Boullanger Bay wetlands. The main objective is to investigate roost habitat choice in shorebirds in the Robbins Passage/Boullanger Bay wetlands and develop a roost-choice model for temperate coastal environments. The model will attempt to identify measurable landscape features that may be used as predictors for shorebird roost sites, and therefore will be valuable in identifying areas of important biological value, to assist in the development of an appropriate wetland-specific management regime.

Method

Study Area

The Robbins Passage/Boullanger Bay wetlands are a coastal intertidal system located in the far northwest of Tasmania (40° 40'S, 144° 50'E) with an area of over 100km^2 and an average tidal range of 3.5m (Fig. 1) (DPIWE, 1999b; Dunn, 2000). The climate in the region is described as cool temperate, with the mean monthly temperatures ranging from 5.1 to 21.8 °C (Appendix 1). Northwest Tasmania is regarded as a windy area, with mean monthly wind speeds of 13 to 30km.hr^{-1}. The wetlands include an extensive area of tidal channels and intertidal sand flats, which encompass approximately 65% of the total site area (Dunn, 2000). The extensive intertidal areas provide feeding habitat for resident and migratory shorebirds. Five species of migratory shorebird occur here in internationally significant numbers: curlew sandpipers (*Calidris ferruginea*), double-banded plovers (*Charadrius bicinctus*), red-necked stints (*C. ruficollis*), red knots (*Calidris canutus*) and ruddy turnstones (*Arenaria interpres*), and two resident species in nationally significant numbers: pied (*Haematopus longirostris*) and sooty oystercatchers (*H. fuliginosus*) (Watts, 1999; Woehler, 2007).

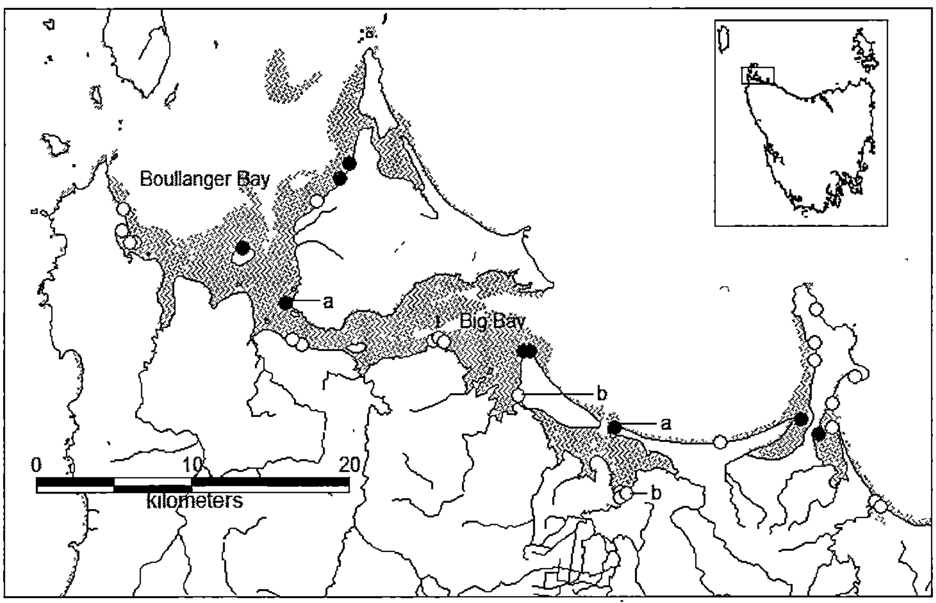

Figure 1. Map of northwest Tasmania showing the location of the roost and non-roost sites. Stippled areas represent tidal flats. • Roost sites, ○ Non-roost sites. a = misclassified roosts, b = misclassified non-roosts.

Data collection

The development of a roost choice model involved the identification of a number of characteristics that are known or believed to be important in the quality of shorebird roosts. Previous studies on shorebird roost selection (Luis *et al.*, 2001; Rehfisch *et al.*, 2003b; Rogers, 2003) allowed the selection of seven variables that were measured at nine roost sites and 23 randomly-selected non-roost sites throughout the wetlands. The variables and their units of measurement are listed in Table 1. These variables can all be related to the two main categories of energy expenditure and predation risk. ASPECT was a measure of exposure of the shorebirds to the elements, predominately wind, while SHELTER was measured as the side of the site that had a barrier to the wind, such as dunes, scrub or bush. DISTANCE TO ROAD was an indication of the amount of disturbance that the shorebirds may be exposed to at a site. DISTANCE TO TALL COVER was measured as distance from roost site to vegetation or landforms greater than 2m. VEGETATION COVER at the site was categorised and classified as bare, sparse, medium or heavy cover (1 – 4, respectively). VEGETATION COVER may be used by the shorebirds for camouflage (or shelter), while tall cover around the site can be used as cover by predators approaching or watching the roost (Rogers, 2003). WIDTH of the site was an indicator of the potential size of the site and was measured as width (perpendicular to the shoreline) available to the shorebirds for use, as many of the sites were bordered by low scrub or sedge grass, which the shorebirds cannot roost in.

Table 1. Environmental variables measured at roost sites and non-roost sites

Variable	Units	Description
Aspect	Degrees from north	Orientation of the site expressed as deviation from north
Shelter	Degrees from north	Orientation of shelter available to the site expressed as deviation from north
Distance to feeding area	Metres	Distance to nearest known feeding area
Distance to tall cover	Metres	Distance to vegetation taller than 2m
Distance to road	Metres	Distance to nearest road or human structure
Vegetation	Categorical (1-4)	Amount of vegetation or tidal wrack covering the site
Width	Metres	Width of the site available to shorebirds

The nine known roost sites (Fig. 1) are all traditional roosts, used consistently throughout the year by migratory and resident shorebird species (Ashby, 1991; Woehler & Park, 2006) (Appendix 2). The roost sites are a combination of sandy beaches and points, and areas of saltmarsh. Non-roost sites were selected randomly, but within areas that were accessible to the investigators. As shorebirds in the region roost in the coastal zone, the location of non-roost sites was restricted to the coastline of the wetlands and extended approximately 5km beyond the wetlands in either direction, ensuring that the sites were selected from areas that were accessible and available to the shorebirds (Jones, 2001). All surveys were undertaken during spring high tides.

Statistical analyses

Habitat variables were normalised and analysed using correlation-based principal components analysis (PCA) to enable identification of patterns in the habitat variables among the sites (Clarke & Warwick, 2001). Univariate analysis was used to identify significant differences among the variables at roost and non-roost sites (Hosmer & Lemeshow, 1989). The mean angle and angular deviation of aspect and shelter at roost sites and non-roost sites was calculated using statistiXL (www.statistixl.com), and compared by means of the Watson-Williams test for two samples with ties (Zar, 1999). VEGETATION COVER was measured as a categorical variable and differences between roost and non-roost sites were tested by G-test of independence (Sokal & Rohlf, 1995). The remaining variables were square-root transformed to achieve a normal distribution and compared with a standard t-test.

To address the issue of collinearity amongst variables, pairs of strongly intercorrelated variables ($r > 0.6$) were considered as estimates of a single underlying factor, as in previous habitat selection studies (Sergio & Bogliani, 2000; Sergio *et al.*, 2004). The variable believed to be more important to the study organisms, or more easily measured, was retained for analyses.

The dependent variable of roost site was dichotomous, with a roost being present (coded as 1) or absent (coded as 0). Therefore logistic regression was used with a forward stepwise procedure to predict the spatial distribution of the shorebirds based on the environmental variables (Hosmer & Lemeshow, 1989). SPSS 14 for Windows was used to calculate the logistic regression and PRIMER 5 (Clarke & Gorley, 2001) for the PCA analysis.

Model evaluation

The predictive accuracy of the model was tested using independent evaluation data collected in southeast Tasmania, approximately 300km from the study site (Fig. 2) (Guisan & Zimmermann, 2000). This evaluation area had a similar number of traditional roost sites used by the same species of migratory and resident shorebirds as the study site (Appendix 2). A threshold value of zero was used to classify the sites, with values greater than zero meaning the site was a roost, otherwise it was coded as a non-roost site. In addition to prediction success (calculating the percentage of locations at which presence or absence was correctly predicted), the discrimination performance of the model was evaluated using the receiver operating characteristic (ROC) curve, a plot of true positive cases against false positive cases across a range of threshold values (Pearce & Ferrier, 2000; Gibson *et al.*, 2004). The area under the curve (AUC) was calculated as a measure of discrimination capacity. This value varies from 0.5 for models with no discrimination ability (no better than chance), to 1.0 for models with perfect discrimination (Pearce & Ferrier, 2000). The ROC analyses were performed using SPSS 14 for Windows, and the AUC calculation was based on a non-parametric assumption.

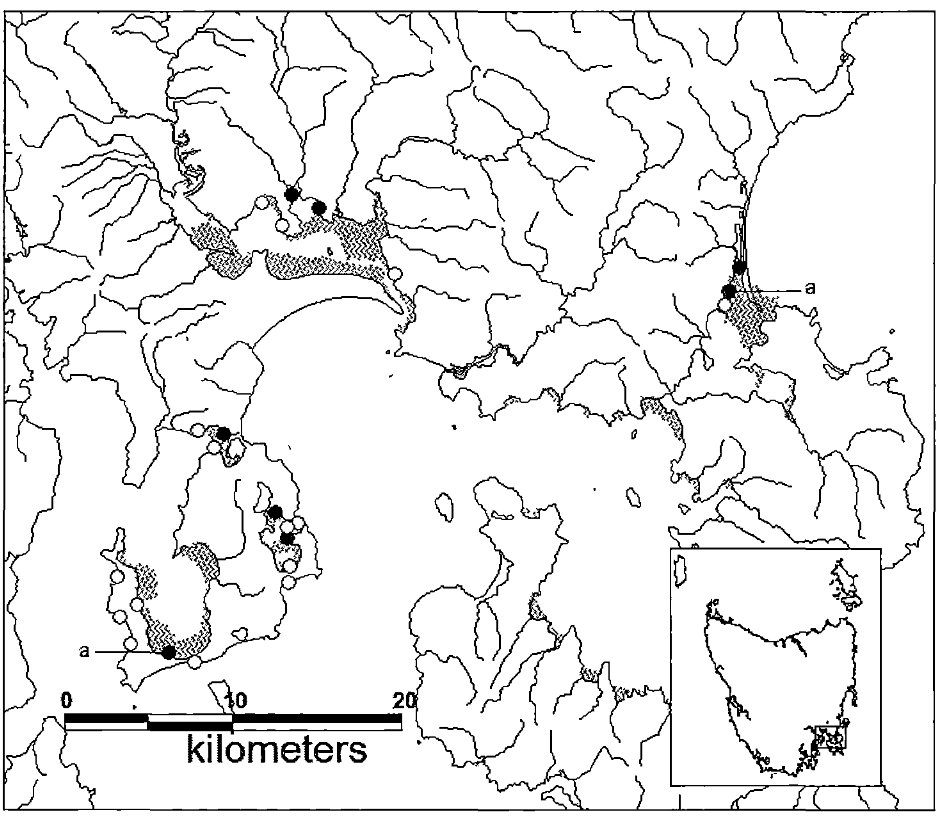

Figure 2. Map of southeast Tasmania showing the location of the roost and non-roost sites. Stippled areas represent tidal flats. • Roost sites, ○ Non-roost sites. a= misclassified roosts.

Results

The first three axes of the PCA of habitat data explained 77% of the total variability among the sites within the Robbins Passage/Boullanger Bay wetlands (Table 2). The PC1 (Fig. 3) axis explained 37.3% of the variance, and was clearly representing decreasing values (from left to right) of DISTANCE TO TALL COVER, DISTANCE TO ROAD and WIDTH, with DISTANCE TO FEEDING AREA having an opposite trend. PC2 (25% of total variance) was best explained as an ASPECT - SHELTER axis, with these variables working in opposite directions. VEGETATION was strongly loaded on PC3 axis (15% variance explained).

Table 2. Eigenvectors of habitat variables on first three axes of PCA

Variables	Principal component axis		
	1	2	3
Aspect		-0.605	-0 355
Shelter		0.657	
Distance to tall cover	-0.531		
Distance to feeding area	0.435		0.437
Distance to road	-0.486		
Vegetation		-0 429	0.689
Width	-0.511		0.349

for clarity, only loadings > 0.3 are shown.

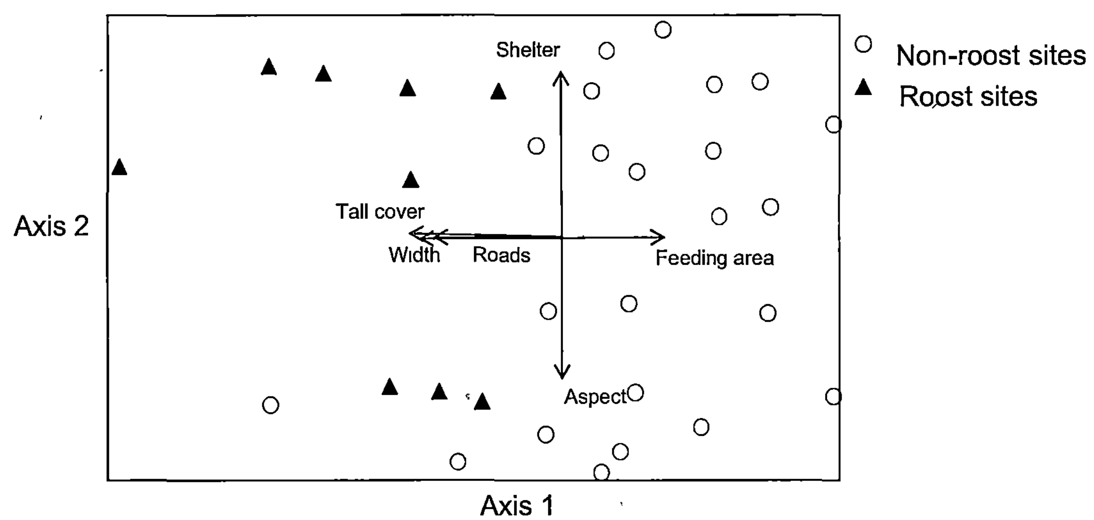

Figure 3. Results of principal components analysis for environmental variables with bi-plot showing variables contributing to separation of points. The length of each arrow is related to the amount of variation that they explain. Results only shown for first two axes, that together explain 62% of the variance. The variables are: Shelter, Aspect, Distance to Tall Cover, Distance to Road, Distance to Feeding Area, and Width.

The univariate analysis showed that four of the seven variables (DISTANCE TO TALL COVER, DISTANCE TO ROAD, DISTANCE TO FEEDING AREA and

WIDTH) were significantly different between roost and non-roost sites (Table 3). Of these four, DISTANCE TO TALL COVER had a strong correlation (> 0.6) with DISTANCE TO ROAD and WIDTH (Table 4). The correlation and univariate analyses therefore reduced the number of variables to be tested for model entrance to three: DISTANCE TO ROAD, DISTANCE TO FEEDING AREA and WIDTH. Of these, DISTANCE TO FEEDING AREA and WIDTH met the entrance criteria for the stepwise logistic regression (Table 5). The Wald χ^2 values of the estimates of the regression coefficients for the two variables indicated that DISTANCE TO FEEDING AREA was the most significant variable for predicting the presence of shorebirds at a known roost site.

Table 3. Means ± SD of environmental variables measured at roost sites and non-roost sites. Univariate differences between the two samples were tested by means of *t* tests. * denotes significance at $p < 0.01$, ** $p < 0.001$.

Variable	Roost sites (n = 9)	Non-roost locations (n = 23)
Aspect[a]	352.4 ± 57.5	357.6 ± 67.3
Shelter[a]	172 4 ± 57.5	138.6 ± 73.9
Distance to feeding area[b]**	500 0 ± 629.8	3906.5 ± 2447.1
Distance to tall cover[b]**	123.8 ± 60.9	46 6 ± 56.7
Distance to road[b]**	3811.1 ± 2635.5	1040.1 ± 2014.5
Vegetation[c]	2.7 ± 0 8	2.9 ± 1.1
Width[b]**	100 0 ± 75.3	32.3 ± 23.5

[a]mean angle is given ± angular deviation. Differences tested by Watson's 2-sample test with ties (see Methods).
[b]*t* test carried out on square root transformed data.
[c]differences tested by G-test of independence.

Table 4. Testing for collinearity of the independent variables. Values indicate the Pearson's correlation coefficients for each variable. * denotes significance at $p < 0.01$. Threshold for collinearity $r > 0.6$.

	Distance to feeding area	Distance to tall cover	Distance to road
Distance to tall cover	-0.452*		
Distance to road	-0.449*	0.696*	
Width	-0.317	0.615*	0.538*

The model was able to correctly classify 77.8% of the roost sites (n = 9) and 91.3% of the non-roost sites (n = 23) for an overall classification rate of 87.5%. The regression equation obtained from the model was:

$$Z = -14.948 - 0.141(\text{DISTANCE TO FEEDING AREA}) + 2.717(\text{WIDTH})$$

The equation suggests a negative association between shorebird roost presence and DISTANCE TO FEEDING AREA, and a positive association between roost presence and WIDTH for the Robbins Passage/Boullanger Bay wetlands. Two roost sites were misclassified as non-roost sites, due to a combination of being among the narrower sites (50m), and being farthest from feeding areas (1000 and 1600m respectively), apart from one other site (1300m)(Fig. 1). Of the misclassified non-roost sites, one was close to feeding areas and on the edge of the width limit (40m), while the other site was also wider (70m), although farther from feeding areas (3000m).

Table 5. Logistic regression of presence/absence of shorebirds on roost sites.

Variable	B	Wald χ^2	p
Distance to feeding area[a]	-0.141	3.344	0.067
Width[a]	2.717	2.387	0.122
Constant	-14.948	2.158	0.142

[a]variable square-root transformed.

Using the independent data set for model evaluation, the model correctly classified 75% of the roost sites and 100% of the non-roost sites (overall = 91.3%). These results indicate that the model was moderately successful in predicting shorebird presence at roost sites. Two roost sites were incorrectly classified as non-roost sites because they were narrower than the roosts in the northwest (15-20m)(Fig. 2). The performance of the model as assessed by the area under the ROC curve (AUC) was 0.976 ± 0.022 indicating that the model could correctly discriminate between shorebird roost sites and non-roost sites 98% of the time.

Discussion

DISTANCE TO FEEDING AREA and WIDTH were identified by the model as the primary variables influencing roost site selection by shorebirds in the Robbins Passage/Boullanger Bay wetlands (Table 5), and the same model was quite successful in predicting the presence of roosts in southeast Tasmania. These variables are related to the two basic requirements of shorebirds: reduction of energy expenditure and minimisation of predation risk. This finding is supported by the roost models developed by Rogers *et al* (2006a) in northwest Western Australia and Peters and Otis (2007) in South Carolina, USA, one of which included distance to feeding area, and the other, roost size. Rogers *et al* (2006a) conducted their study in tropical north-west Australia, based on red and great knots (*C. canutus* and *C. tenuirostris*). Their study tracked individual birds, investigating roost choice at a different level. They found that their models performed differently under neap tide and non-neap tide conditions and that different models were required to predict roost choice by day and night. By day, distance from feeding area and microclimate affected roost choice, whereas at night, distance to tall cover was more important (Rogers *et al.*, 2006a).

DISTANCE TO FEEDING AREA has been previously shown to be one of the most important variables influencing roost choice (Furness, 1973; Swennen, 1984; Rehfisch *et al.*, 2003b), allowing the shorebirds to minimise energy expenditure in moving between their roost and feeding areas (Furness, 1973; Piersma *et al.*, 1993a). The shorebirds must conserve as much energy as possible, as they build up fat reserves for moulting, migration and breeding. Van de Kam *et al.* (2004) suggested that shorebirds expend an extra 1.3% of energy reserves for every extra kilometre they fly between roost and feeding sites, and that this makes little difference if the bird has to fly an extra few kilometres. However, Rogers *et al* (2006b) calculated that commuting flights for red and great knots in northwest Western Australia accounted for 2.3-8.5% of the total energy expended. Any extra energy expenditure due to longer flights to feeding areas, could affect the birds overall fitness, especially over increasing lengths of time. A variety of shorebirds have been shown to move relatively short distances (< 3km) between roosts and feeding sites (Kelly & Cogswell, 1979; Warnock & Takekawa, 1996; Pearce-Higgins, 2001) and this is most likely related to conserving energy (Warnock & Takekawa, 1996). As Dias *et al.* (2006a) and Rogers *et al* (2006b) found, it is possible that the use of feeding areas is constrained by lack of suitable high-tide roosts, thereby limiting the overall suitability of entire estuaries to migratory shorebirds.

In South Carolina, Peters and Otis (2007) found that roost length (size), local region, substrate and aspect influenced roost selection for eight species of shorebird on an annual scale, while daily roost use was influenced by wind speed and shelter. Our findings that wider sites are preferred as roosts are consistent with Peters and Otis (2007). A larger roost site may allow more birds to roost, thereby providing a number of benefits: increased predator vigilance (Burton *et al.*, 1996; Roberts, 1996; Rosa *et al.*, 2006) and decreased risk of predation through the "dilution" effect (Rogers, 2003), and physiological advantages through flocking and decreased energy spent on thermoregulation (Ydenberg & Prins, 1984; Rogers, 2003).

However, WIDTH may also be acting as a surrogate variable for DISTANCE TO TALL COVER, since there was a significant correlation between the two in Robbins Passage/Boullanger Bay (r = 0.6). Tall cover surrounding a roost site can be used as potential cover for an approaching predator (Rogers, 2003). In Tasmania, the main predators of shorebirds at roost sites are birds of prey, such as peregrine falcons (*Falco peregrinus*). Some distance between the roost site and tall trees or dunes allows shorebirds more time to detect an approaching predator and take evasive action. If the risk of predation at a roost site is low, birds can also be expected to spend less time in vigilance behaviour (Rosa *et al.*, 2006).

The northwest coast of Tasmania is a relatively windy area with the wind predominately from the west and southwest (unpubl. data). As wind appeared to be the climatic factor that affected the birds the most (FS pers. obs.), it was thought that the shorebirds may roost in sheltered locations to limit the energy used in thermoregulation. During high wind periods (> 30km/hr), the birds were observed roosting in tight flocks and behind tidal wrack and small sand hummocks on the beach. However, ASPECT and SHELTER were not significantly different between roost and non-roost sites, perhaps because they were too indirect as measures of exposure, or measured at a scale that did not record the features actually used by the birds for shelter. Further investigations would be required to determine whether microclimate is a factor in roost choice in Robbins Passage/Boullanger Bay wetlands. The local climate makes it seem unlikely that heat stress would be an important factor, as it was in northwest Western Australia (Rogers *et al.*, 2006a).

Predation risk is thought to be one of the primary determinants of roost site choice (Rehfisch *et al.*, 2003b; Rogers, 2003; Rosa *et al.*, 2006), with a number of studies finding that shorebirds use different roosts at night to avoid night time predators (Hockey, 1985; Handel & Gill, 1992; Rogers *et al.*, 2006a). In New South Wales, Rohweder (2001) found that shorebirds used more exposed roost sites during the day, perhaps to avoid day time predators, such as raptors. Although this study did not investigate night roost use, the shorebirds in Tasmania would also be primarily concerned with daytime predators, although cats and quolls may be potential night-time predators.

Disturbance is considered an important determinant of roost site selection (Furness, 1973; Luis *et al.*, 2001; Rehfisch *et al.*, 2003b). If the shorebirds are disturbed, the whole flock, or at least part of it, takes flight, utilising valuable energy resources. If a site is regularly disturbed, the shorebirds may be forced to abandon it and find an alternative (Mitchell *et al.*, 1988; Burton *et al.*, 1996). DISTANCE TO ROAD was the variable used in this study as an indicator of disturbance in the roost selection model. Roost sites were significantly farther from roads than the non-roost sites. However, this factor did not meet the selection criteria for entry into the model (see Statistocal analysis, Methods section).

In the current study area, there was a restricted number of sites where the shorebirds were present ($n = 9$), limiting the number of variables that could be used in the modelling process (Stolzenberg, 2004). Our *a priori* decisions regarding variable entry into the model, limited them to three, resulting in a moderately successful model. There are certainly additional variables influencing roost-site selection, but a larger number of active roost sites would be required to determine which of these are important. Since it is in another region, we did not choose to include the independent data set from southeast Tasmania in the model building, electing to use it for the model evaluation, a crucial step in ecological modelling studies (Guisan & Zimmermann, 2000). The evaluation demonstrated that the model was effective in other temperate coastal regions and its predictive success was high (AUC = 0.976).

A small number of cases were misclassified by the model (12.5% in the training data and 8.7% in the evaluation data). The model implies that if a site is wide enough and within reasonable range of a feeding area, it may be acceptable as a roost site. There may be feeding areas in the Robbins Passage/Boullanger Bay wetlands of which we are presently unaware, that could explain the misclassification of some roosts as non-roost sites. The non-roost sites misclassified as roost sites were within range of feeding areas, and were also an 'acceptable' width. While these sites fulfil the model criteria, they are not used by the shorebirds, either because there are better sites available (traditional sites) or because these sites are unacceptable for some other reason. Of the two non-roost sites classified as roost sites, one backed onto a road and was close to tall cover (30m); the other site appeared acceptable as a roost, but there was a traditional roost nearby (2500m), closer to the feeding areas (Fig. 1).

The width of the site is the determining factor in roost selection on coastline that is adjacent to feeding areas. Within the Robbins Passage/Boullanger Bay wetlands, much of the coastline is relatively narrow (<5m at high tide) and bordered by relatively dense scrub (FS pers. obs), making the few available wide high tide sites valuable to the shorebirds.

While many habitat selection studies expand into habitat mapping using geographical information systems (GIS) (Franco *et al.*, 2000; Jaberg & Guisan, 2001; Gibson *et al.*, 2004), the resolution of available GIS layers for the study area proved to be too coarse, especially the vegetation layer, to predict sites available for shorebird use. Ground surveys and detailed mapping would be needed to determine how much of the coastline fits within the model's criteria, and may be a consideration for further studies in these wetlands.

Conclusion

This study showed that shorebirds choose their roosts based on distance to their feeding area and width of the roost site. This reflects a need to minimise energy expenditure and reduce predation risk, as explained earlier. The distance of the roost from the feeding area was the most significant variable, enforcing the fact that shorebirds must be able to roost within a certain distance of their feeding area or they abandon that area (Dias *et al.*, 2006a; Rogers *et al.*, 2006b).

Further work is necessary to improve the predictive power of the present model, and should include increased knowledge of shorebird movements among roosting and feeding areas in the Robbins Passage/Boullanger Bay wetlands, and identifying and confirming the remaining feeding areas within these wetlands. It would also be necessary to resample areas where presence was incorrectly predicted, and other sites in the wetlands that fulfil the model criteria but are not used as roosts, in an attempt to determine what other variables may be used to improve the model, e.g. substrate type. The model may also be improved by investigating species-specific roost use. This information will assist in the management and conservation of the wetlands for shorebirds and ensure the preservation of suitable roosting places throughout the wetlands.

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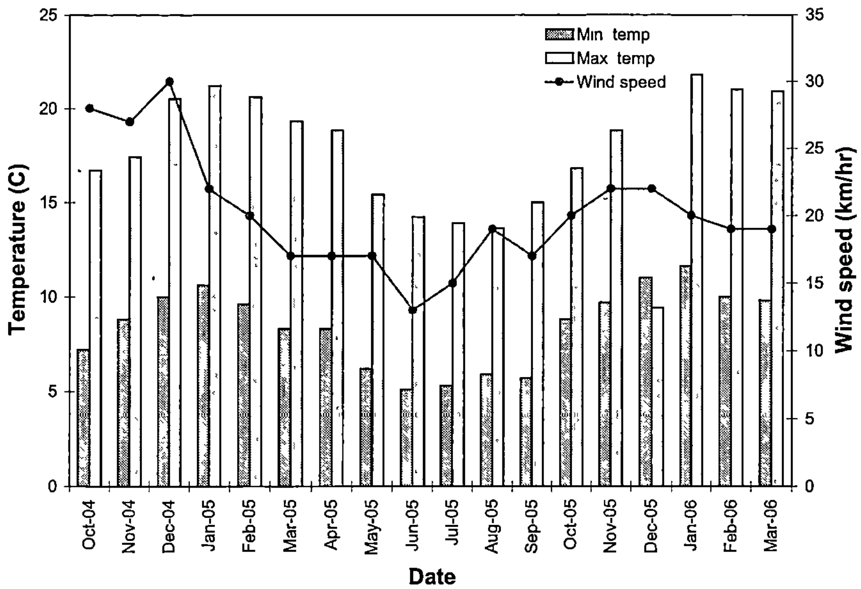
Appendix 1. Mean monthly minimum and maximum temperature and wind speed for Smithton, northwest Tasmania, during the field season.



Appendix 2. Traditional roost sites in Robbins Passage/Boullanger Bay wetlands used for the roost model and in southeast Tasmania used for roost model validation, and the maximum number of shorebirds and shorebird species at each roost (2004-2006).

Robbins Passage wetlands			Southeast Tasmania		
Roost	Max. number of birds	Number of spp.	Roost	Max number of birds	Number of spp.
Shipwreck Point east	4393	20	Pipeclay Lagoon and Pipeclay Lagoon A		7
Shipwreck Point west	273	10	Lauderdale		5
Kangaroo Island	4261	12	South Arm Neck		8
Wallaby Island	417	7	Cemetery Point		5
West Anthony's Beach	1194	10	Orielton Lagoon		11
East Anthony's Beach	720	11	Marion Bay – Porpoise Hole and Little Boomer		9
Bird Point	4720	16			
Knot Point	5741	14			
East Inlet	580	3			

Chapter 7

General Discussion

Introduction

Virtually all species of shorebirds are decreasing on a global scale, due primarily to habitat loss and/or modification (IWSG, 2003; Birdlife International, 2004b). Habitat loss and modification are amongst the most serious consequences of human development, and the coastal zone is one of the regions under the most serious threat, through wetland reclamation, increased coastal erosion, decreased water quality and the threat of rising sea levels through climate change (Finlayson & Mitchell, 1999; Finlayson & Rea, 1999; Kennish, 2002; IWSG, 2003; Birdlife International, 2004b).

Many shorebirds are migratory and travel through a number of countries, moving between their breeding grounds and winter feeding areas. Therefore, management plans to conserve and protect the shorebirds must be developed and agreed by all the relevant countries. In order to develop these management plans for shorebirds, critical fundamental data on their habitat requirements and energy needs are required. Tasmania is at the southern-most end of a migratory route that travels almost the length of the earth, and is therefore of national, and international, importance for shorebird habitat.

The broad aim of this study was to investigate how shorebirds use the resources of coastal wetlands at a local regional scale within the Robbins Passage/Boullanger Bay wetlands, with a view to providing information for the appropriate management and conservation of shorebirds and the wetlands. In order to achieve this, the habitat use of feeding and roosting shorebirds was investigated and the relationships with physical, environmental and biological variables examined. The study also developed the first roost choice model for shorebirds in temperate Australia.

Detailed discussions of these studies have been presented in previous chapters (Chapters 2-6), but the key findings and their significance will be summarised briefly here. This chapter then discusses their implications for shorebird management, concluding with a summary of possible future studies into shorebird research within the Robbins Passage/Boullanger Bay wetlands.

Key findings

Shorebird feeding habitat

In chapters 2-4, the feeding distribution of shorebirds within and among tidal flats was investigated, and the factors that may influence it, including macroinvertebrate distributions, abundances and biomass, and environmental variables including seagrass biomass, sediment composition and organic carbon content.

Within the Robbins Passage/Boullanger Bay wetlands, shorebirds exhibited preferences for certain low-tide feeding areas, with the greatest shorebird densities and abundances observed at Shipwreck Point and East Inlet, the sites with the greatest invertebrate densities, and the greatest invertebrate biomass and species diversity, respectively (Chapters 2 & 3). Of the four study sites investigated in this study, Palaearctic shorebirds were found only at Shipwreck Point and East Inlet, and of these Shipwreck Point had the highest number of shorebird species (resident and migratory combined). Shorebirds generally foraged at the low intertidal stratum and at the water's edge, where invertebrate biomass was greatest, although shorebird foraging patterns were to some extent species-specific.

The shorebird's choice of feeding area was driven primarily by invertebrate biomass and invertebrate species diversity, and environmental factors (seagrass biomass and tidal flat area). The effects of seagrass biomass on the density of feeding shorebirds was dependent upon their feeding method; probing shorebirds, especially pied oystercatchers, had a tendency to feed where the mass of seagrass leaves was low, such as the low intertidal stratum and at the water's edge. Ruddy turnstones, Pacific golden plovers and hooded plovers tended to feed where seagrass root mass was higher, in the mid-intertidal stratum. This may have been because seagrass biomass influenced invertebrate community composition, and with increasing seagrass biomass there was an increase in invertebrate abundance and invertebrate species diversity.

While some studies have shown that sediment particle size can be used to predict shorebird feeding densities (e.g. Yates *et al.*, 1993; Kalejta & Hockey, 1994), this was not the case in this study, and it is doubtful that any single physical environmental factor or measure of the tidal flats in Robbins Passage/Boullanger Bay wetlands could be used to predict shorebird feeding density with any confidence. Overall, the spatial scale of the analyses influenced the strength of the relationships between shorebird density and environmental and prey variables, with a stronger relationship observed on a larger spatial scale. However, it is clear that different habitats and tidal strata appeal to different species of shorebird, making it difficult to say that any one habitat is of primary importance.

Although not examined in this study, predation risk is an important factor governing choice of foraging sites for shorebirds. Some studies have found that shorebirds feeding at stopover sites during their migration may accept a higher risk of predation in favour of higher feeding rate (Ydenberg *et al.*, 2002). Ydenberg *et al* (2002) observed that sandpipers stopping over in Canada fed at two separate sites, one with a low predation risk (wide tidal flat and very open) and the other a higher predation risk (narrow tidal flat with cover close by). It was found that shorebirds were making a trade-off between feeding rate and predation risk. The leaner shorebirds fed at a site with a higher feeding rate to enable them to fatten up more quickly. The hypothesis also assumes that leaner birds are less vulnerable to predation, as they can move more quickly (Dierschke, 2003). This may not be such an important issue at a wintering site, but should be considered in future studies on habitat quality and roost choice in the Robbins Passage/Boullanger Bay wetlands.

While counting feeding shorebirds at low tide ensures that all the shorebirds are present on the tidal flats, habitat use over the tidal cycle may vary. Shorebird habitat use during the ebbing tide concurred with low tide habitat use, with the greatest densities and numbers of shorebirds occurring at both Shipwreck Point and East Inlet, the only sites where Palaearctic shorebirds were found (Chapter 4). Shorebird density did not vary significantly during the ebbing tidal cycle, although shorebird abundances did vary at two of the four sites, with greater numbers occurring two hours and four hours before low tide. For the purpose of this study, low tide counts were sufficient to allow identification of important feeding sites and comparisons between sites; however, if logistics and resources allow, future studies should include a mid-tide survey in addition to a low tide count, to ensure a more complete survey of the wetlands.

Shorebird roosting habitat

Shorebirds utilise nine known traditional roost sites within the Robbins Passage/Boullanger Bay wetlands, and the four roosts with the highest numbers of shorebirds over the last four years (in no particular order) were Shipwreck Point, Kangaroo Island, Bird Point and Knot Point/Five Islets (Fig 1). Three of these roosts are on the west coast of Robbins Island, while Shipwreck Point is on the northeast coast of Perkins Island. These roosts are used by Palaearctic and resident shorebirds and are considered the primary roosts for the Palaearctic shorebirds. Robbins Island is privately owned and currently used for winter cattle grazing, as is Perkins Island, which is leased to a local landowner. Access to both islands is usually by driving across the sand flats at low tide, and permission from the owner/leasee is required. This is of some benefit to the shorebirds, although private ownership of the land may make it difficult to effectively manage these areas.

At the four roosts which were investigated for this study, East Shipwreck Point, West Shipwreck Point, East Anthony Beach and West Anthony Beach, there was a high seasonal variation in the numbers of roosting shorebirds, due primarily to migration of Palaearctic shorebirds, and the breeding season of the resident species (Chapter 5). The greatest numbers of roosting shorebirds occurred during the summer months, December to February, when the Palaearctic shorebirds arrived from their northern breeding grounds. The arrival in autumn (March – May) of double-banded plovers from New Zealand also resulted in a peak in shorebird numbers at one of the sites, West Anthony Beach. The resident shorebirds were present at the roost sites in greatest numbers during the autumn, after they had completed their summer breeding seasons.

The numbers and species of shorebirds at each roost site also varied, with East Shipwreck Point accommodating more than six times the mean number of birds than at other sites. Some roost sites therefore hold more appeal than others, although these patterns of use may be short-term. The roost choice model developed in Chapter 6 showed that there was a tendency for roosting sites to be close to feeding areas and wide enough to provide some distance between birds and potential cover for predators, allowing the birds to detect approaching predators in time to react (i.e. escape). While the modelling in this study showed that there are other sites that may be acceptable as roost sites within the wetlands, the shorebirds selected the sites that best fulfilled their needs, in that they may be slightly closer to the preferred feeding area, or slightly farther from cover for possible predators. Other roost studies have found similar findings to this study, in that sites with factors that reduce energy expenditure and predation risk are preferred (e.g. Luis *et al.*, 2001; Rogers *et al.*, 2006a).

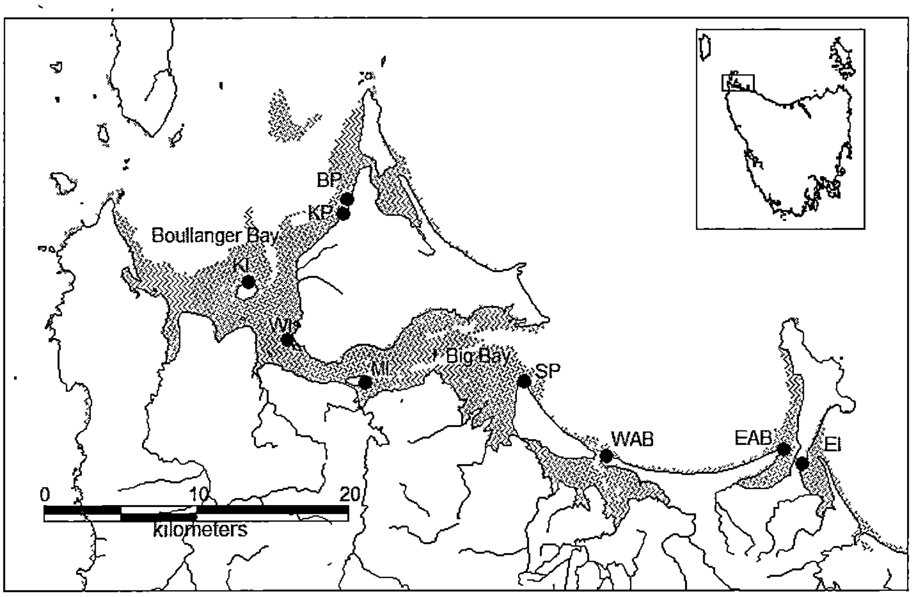


Figure 1. Location of traditional roost sites within the Robbins Passage/Boullanger Bay wetlands. (BP - Bird Point, EI - East Inlet, EAB – East Anthony Beach, KI – Kangaroo Island, KP – Knot Point, MI – Montagu Island, SP – Shipwreck Point, WAB – West Anthony Beach, WI – Wallaby Island)

The examination of summer and winter shorebird roost counts at the Robbins Passage/Boullanger Bay wetlands and two wetland complexes in Victoria - Werribee and Westernport Bay - showed that while there was annual variation of shorebird abundance at roost sites, there were also some similarities in these variations between the sites (Chapter 5). And while it has been shown that breeding success of certain species is correlated to winter roost counts in south-east Australia (Minton *et al.*, 2005), this is not quite so clear for northwest Tasmania. Some patterns were observable, particularly for red-necked stints, but a more thorough data set may be necessary before a significant relationship is determined between winter count and breeding success.

However, to enable roost count data to be utilised to monitor fluctuations in the shorebird population, the entire wetland must be counted, not just a small number of roosts, as shorebirds readily move among roost sites (Rehfisch *et al.*, 2003b) and incomplete counts may be biased and lead to incorrect conclusions. This highlights the importance of the biannual wader counting efforts in Tasmania and Victoria, which are organised by Birds Tasmania and the Australian Wader Study Group respectively, and undertaken by numerous and dedicated volunteers.

Review of shorebird habitat studies

While shorebirds have been subject to study for many years (e.g. Goss-Custard, 1970; Thomas & Dartnall, 1971; Evans, 1976; Goss-Custard *et al.*, 1977b), the increasing concern about their habitats and decreasing population numbers is reflected in the growing number of studies on shorebird habitat use and the identification of biotic and abiotic factors that influence shorebird densities on wetlands (e.g. Goss-Custard, 1979; Piersma *et al.*, 1993b; Kalejta & Hockey, 1994; Jing *et al.*, 2007 as recent examples). Studies investigating aspects of shorebird ecology in the northern hemisphere (e.g. Goss-Custard *et al.*, 1977b; Zwarts, 1981; Townshend *et al.*, 1984) have led the way for similar studies in Australia, most notably in north-western Western Australia, where red and great knots in particular are being studied (Tulp & de Goeij, 1994; Rogers, 1999; Piersma *et al.*, 2002). While these studies are location-specific, as is the present one, they all provide greater understanding of shorebirds and their requirements, especially during migration and at the winter feeding grounds. This study attempted to go a step further by investigating feeding and roosting habitats for the general shorebird population, rather than species-specific studies, to allow general guidelines regarding essential shorebird habitat to be incorporated into regional management plans.

The factors affecting shorebird feeding density are generally agreed to be the abundance or biomass of their invertebrate prey, while other factors are either related to the shorebirds feeding method, or directly to invertebrate abundance and biomass, e.g. sediment particle size, seagrass cover and tidal flat area (Goss-Custard *et al.*, 1977b; Quammen, 1982; Moreira, 1993; Finn *et al.*, 2007). The variables influencing shorebird roost choice have until recently received less attention, and may be more location-specific, with tropical regions more likely to be influenced by substrate temperatures (Rogers *et al.*, 2006a). In general, it appears that proximity to feeding areas, disturbance and risk of predation are the fundamental drivers for shorebird roost choice (Rehfisch *et al.*, 1996; Luis *et al.*, 2001; Rogers *et al.*, 2006a; Rosa *et al.*, 2006), based on existing studies.

Overall, the important characteristics of any site at the large scale are that within it the birds are able to acquire a positive energy balance through feeding at a site with an abundant and predictable supply of food, and then maintain that energy balance, by roosting at a site where they are not disturbed or caught unawares by predators.

Implications for management

On a local scale, several implications for management of the Robbins Passage/Boullanger Bay wetlands arise from this study. First, the highest numbers of shorebirds are present in the Austral summer, when human presence and activity in the wetlands and surrounding areas are also at their highest. This highlights the need for appropriate management and protection of important shorebird areas to ensure they are protected from disturbance or habitat modification, particularly at this busy time of year. This is more difficult in some areas than others, as two of the roost sites, West and East Anthony Beach are on the respective ends of a popular local beach that is utilised intensively for four-wheel driving, quad bike riding, horse riding and fishing (Spruzen, 2005).

Second, land-use within the wetland's catchment areas must also be monitored closely to ensure that inflowing water quality is maintained within the wetlands through sustainable land practices. Seagrass was shown to be an important environmental factor in the feeding areas of some shorebirds and the general ecology of the wetland, and increased sediment runoff and turbidity are detrimental to its survival (Edgar, 2001).

Third, it is clear that shorebirds use a variety of different habitats for roosting and feeding, and the loss of these locations through disturbance or modification may result in the loss or decrease of shorebirds from the wetlands (Burton *et al.*, 1996). It is believed that all of the major or primary shorebird roost sites within the Robbins Passage/Boullanger Bay wetlands have been identified, but the primary feeding areas are less well identified, and disturbance on the feeding grounds, if any, through oyster farming needs to be determined. It is critical that the variety of habitats used by shorebirds within the wetlands are protected, to ensure that the diversity of shorebirds that visit the area is maintained into the future.

Appropriate management techniques to manage these threats and issues should include:

- providing and enforcing buffer zones around the roosts by fencing off either end of Anthonys Beach during the busy summer months (Nov-Apr);
- preventing vehicle access to Anthony Beach and the northern side of Perkins Island during the summer months (Oct- Apr), which would also be beneficial to resident breeding shorebirds;
- monitoring water quality in the waterways draining into the wetlands (e.g. Duck, Montague and Welcome Rivers), and implementing and enforcing effluent strategies for dairy farms in the area; and
- continuing monitoring studies in the area and ensure all known roost sites are counted for the summer and winter roost counts.

Finally, nomination of the Robbins Passage/Boullanger Bay wetlands as a Ramsar site would provide further recognition of the international shorebird values of the area and would encourage the local community to take greater stewardship of the area.

The results of the roost modelling are likely to apply to other temperate coastal estuaries world-wide and allow us to identify potential roost sites in a wetland. It may also allow the correct placement of artificial roost sites when this becomes absolutely necessary, as several studies have shown that artificial roosts are a successful form of management in replacing roost sites lost due to land reclamation (e,g, Burton *et al.*, 1996; Rehfisch *et al.*, 2003b).

This study has contributed to the growing body of information available concerning shorebird habitat use, and provided a new model in addition to enhancing existing ideas. The study has also provided a baseline for further studies in the Robbins Passage/Boullanger Bay wetlands.

Future studies

While this study has determined habitat criteria for roosting shorebirds within the Robbins Passage/Boullanger Bay wetlands, and has identified environmental and prey variables influencing their feeding density, it is essential to gather as much information as possible about this area. Clearly, the biannual surveys of roost sites should continue, endeavouring to count simultaneously all nine roost sites on each occasion, to enable the identification of any trends in roosting shorebird numbers. These long term data sets will provide a context for any and all future research efforts in the wetlands. Assuming that no further major roosts remain to be discovered, the first priority for new work is to confirm and identify all the shorebird feeding areas within the wetlands, including major areas suspected to the west of Robbins Island. One approach that should be considered is the use of radio or satellite tracking on a number of shorebirds of various species. This would allow the identification of feeding areas, increase knowledge of shorebird movements within and among feeding areas during the tidal cycle, their movements among feeding areas and roost sites, and determining roost site fidelity and inter-roost movements. Once the feeding sites have been identified, invertebrate sampling would need to be undertaken to refine our knowledge of the resources being used by the birds. While shorebird prey studies in other areas can provide indications of the preferred prey of shorebird species, the main prey taxa and prey sizes of the primary shorebird species within these wetlands should be identified, to allow further investigations into the relationships among invertebrate abundances and biomass with shorebird feeding densities.

To investigate larger-scale movements, leg flagging of shorebirds could be used to allow sighting of these marked shorebirds at other wetlands. This information may be important in determining whether northwest Tasmania is part of a larger complex, including wetlands in southeast Victoria, among which shorebirds move within a summer. It would also be useful to age the birds while handling them for leg flagging, as adults or juveniles, to determine the proportions of juveniles of each species that come to northwest Tasmania. These data could be compared with comparable data from elsewhere in Australia, providing insight into intra-Australia migration and habitat use at continental scales.

Finally, comparable studies in southeast Tasmania, where migratory and resident shorebirds are present in lower numbers (but for which longer data sets are available) would further improve our knowledge of shorebirds in Tasmania, and its contribution to shorebird migration within the East Asian-Australasian Flyway.

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